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**Final Proceedings of
The EOARD/IRC-sponsored
International Workshop on Gamma
Aluminide Alloy Technology**

held from 1 to 3 May 1996
at The IRC in Materials for High Performance
Applications
The University of Birmingham

SECTION THREE

The organisers wish to thank the United States Air Force European
Office of Aerospace Research and Development for its contributions to
the success of this conference

20000223 173

Interdisciplinary IR Centre

in

Materials for High Performance Applications

**Final Proceedings of
The EOARD/IRC-sponsored
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Aluminide Alloy Technology**

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Applications
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SECTION THREE



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298-102

Gamma Alloy Technology: Fundamentals and Development

Young-Won Kim

UES-Materials & Processes

Dayton, OH, USA

Fundamentals

Processing

Microstructural Evolution

Structure/Property Relationships

Designing Microstructures

Component-Specific Alloy Design

Forming and Application

Summary and Future Direction

(April 1996)

Fundamentals

Phase Relations and Transformations

Microstructural Evolution

Deformation Mechanism

Alloying Effects

Deformation and Fracture Behavior

Environmental Resistance

Alpha Decomposition

At Very Slow Cooling Rate

At Intermediate Cooling Rates

- Lamellar Structure Formation

 - Stacking Fault Mechanism
 - Gamma Precipitation and Growth

- Ordering

 - No Compositional Changes Involved
 - Compositional Changes Involved

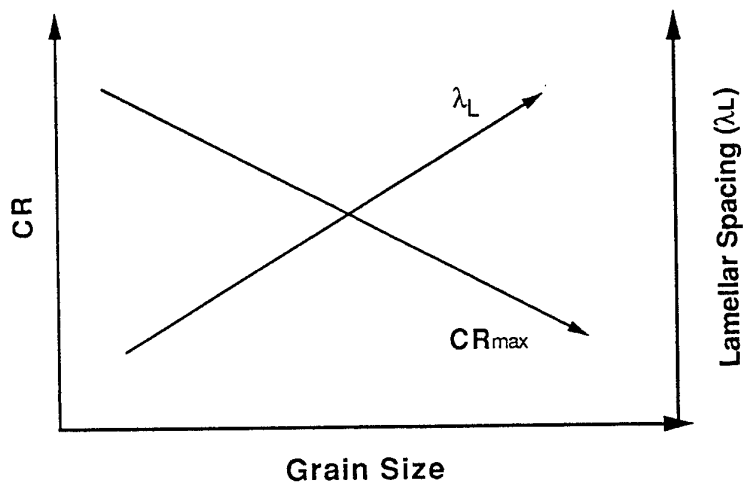
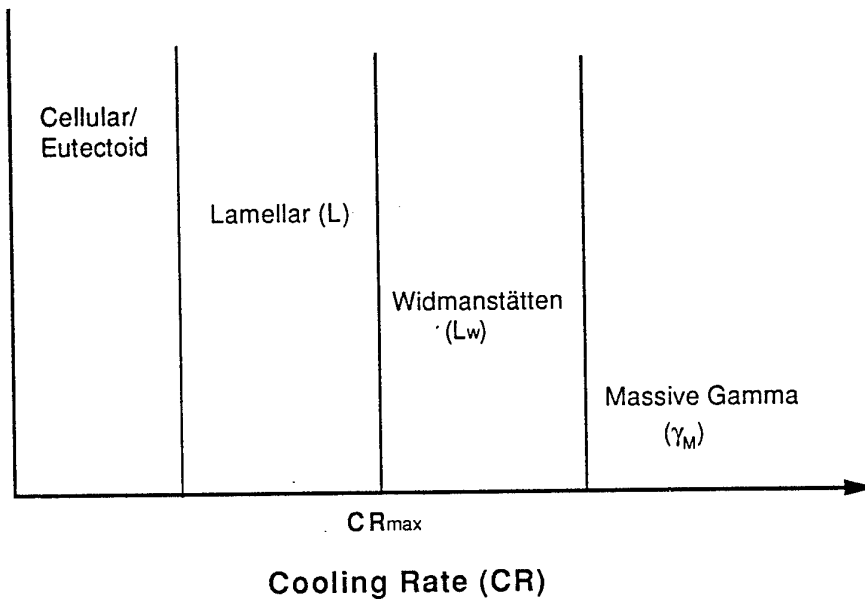
- Effects of Composition and Cooling Rate

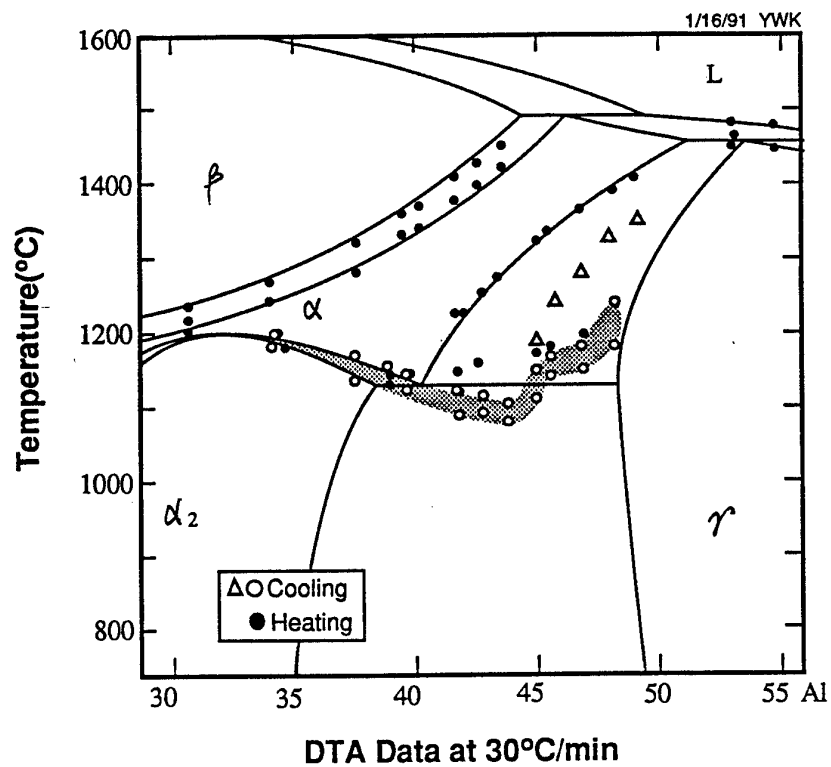
At Fast Cooling Rates

- Widmanstätten Structures

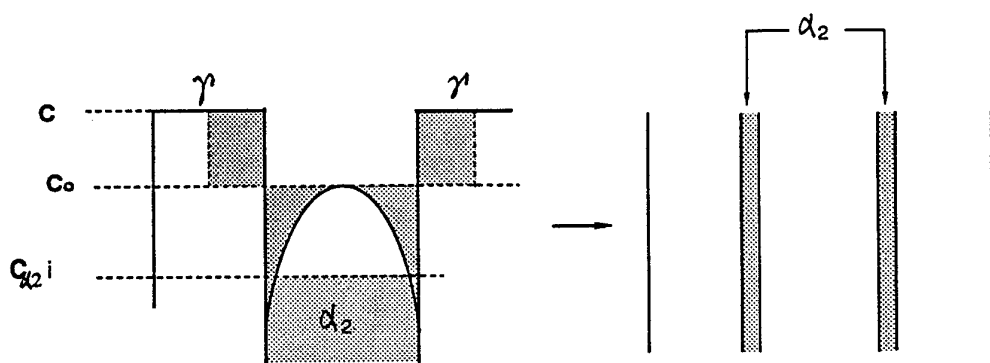
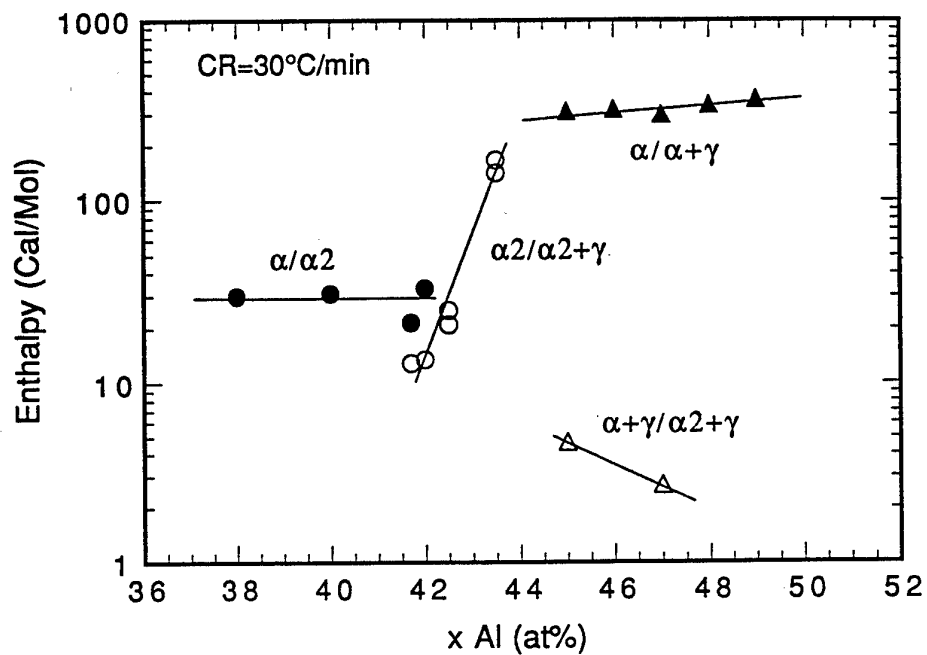
- Massively-Transformed Gamma

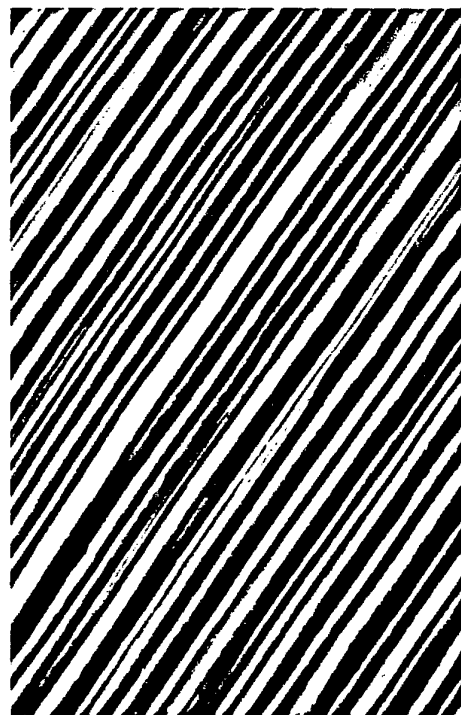
- Formation of α_2 Phase





Transformations of Alpha Phase in Ti-xAl



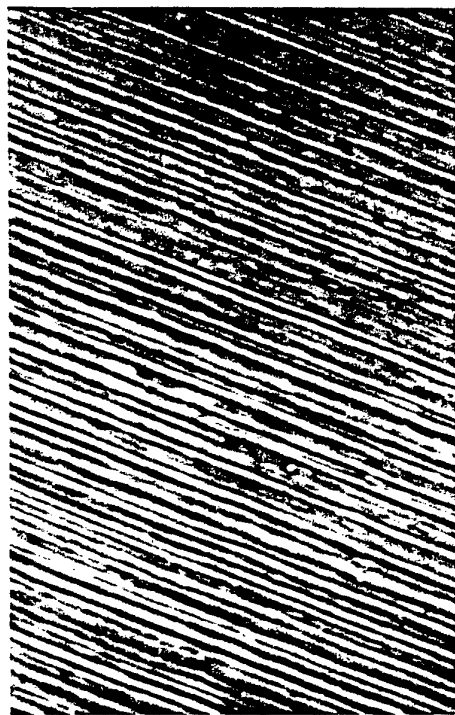


1°C/min

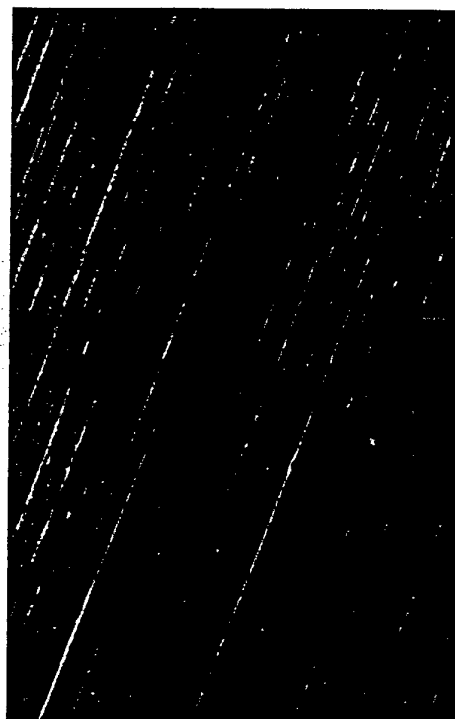
5 μ m



3°C/min



20°C/min

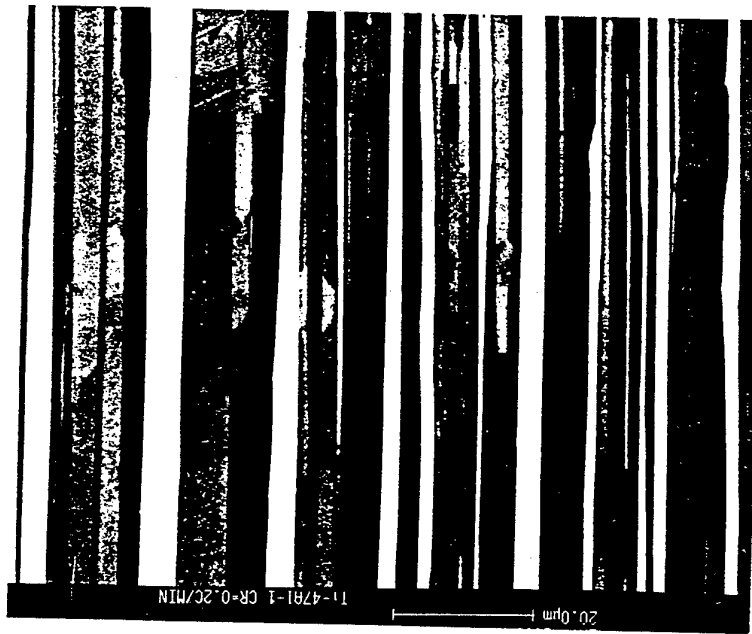


100°C/min

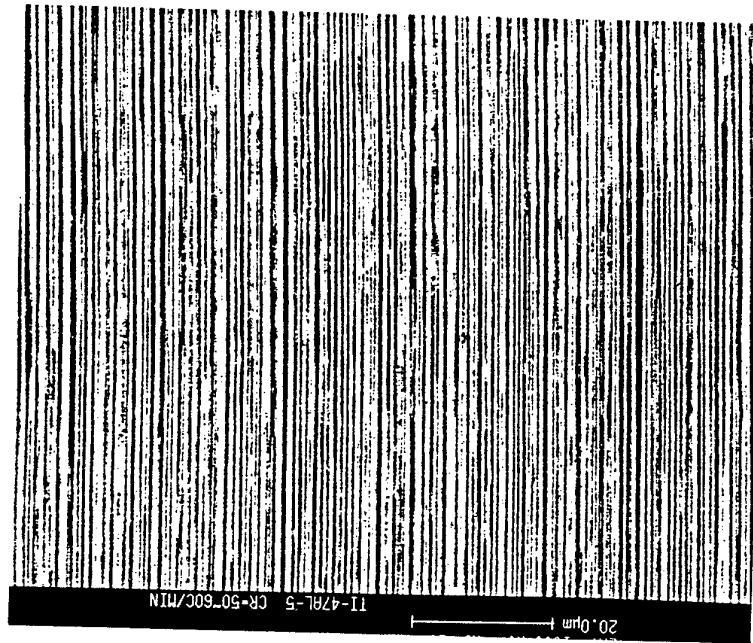
Ti-43Al : Homogenized and DTA Cooled

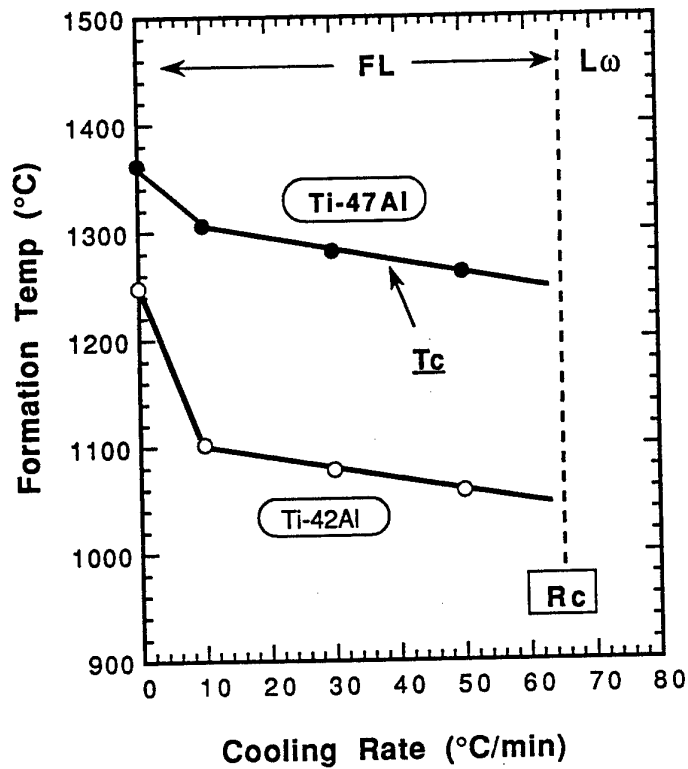
Cooling Rate vs Lamellar Spacing (Ti-47Al)

0.2 °C/min



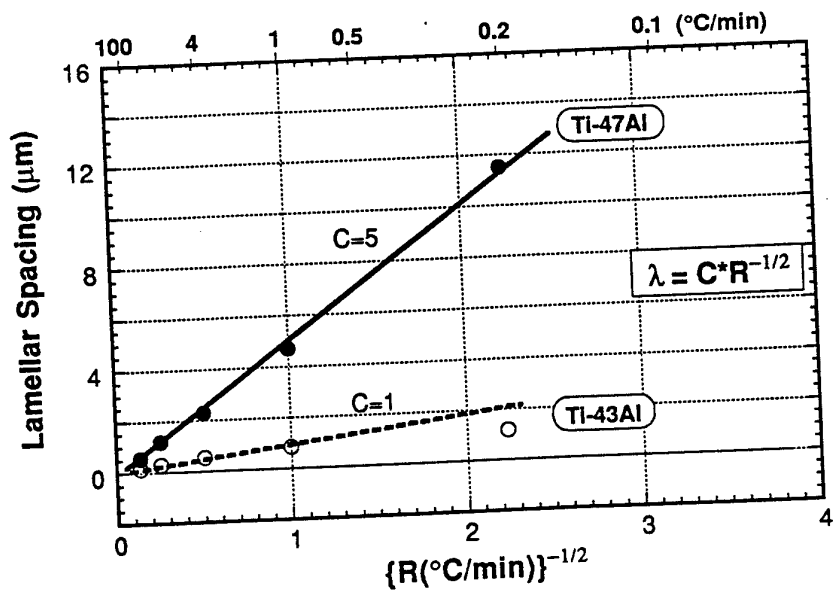
50 °C/min





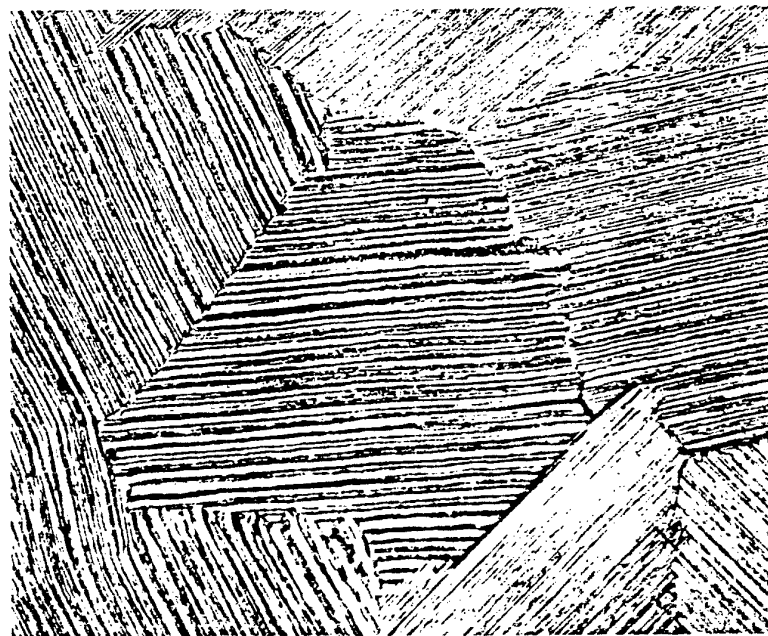
Kim (94)

Cooling Rate (R) vs Lamellar Spacing (λ)



Kim (94)

50μm



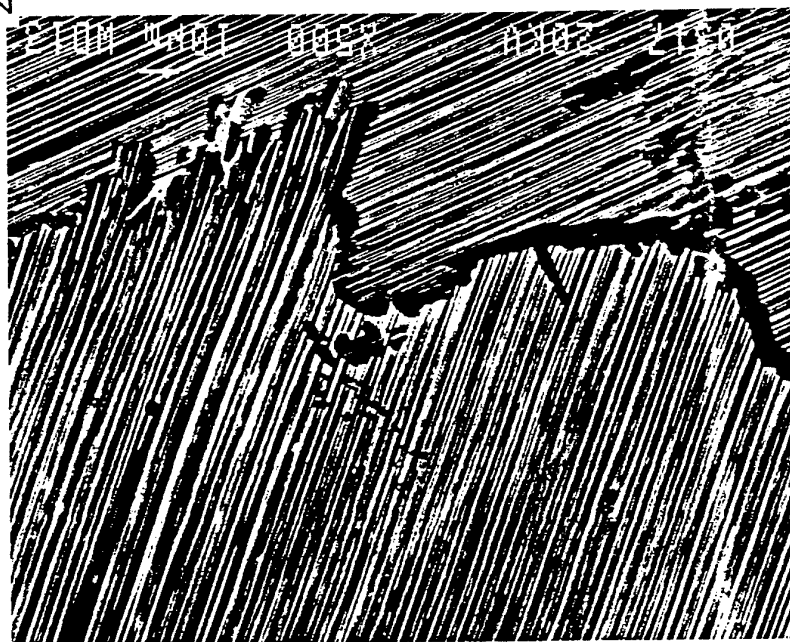
TI-43AL: COOLED AT 5°C/MIN



TI-47AL: COOLED AT 30°C/MIN

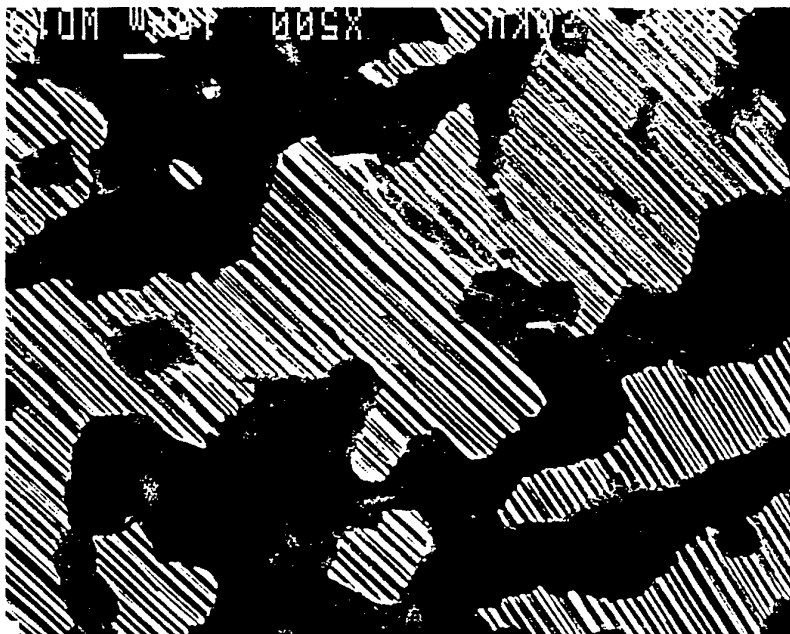
DTA SPECIMENS OF HOMOGENIZED ALLOYS

20μm



Ti-47Al-1.1 wt%Ox

1350°C/6 hr + 1000°C/24 hr/WQ



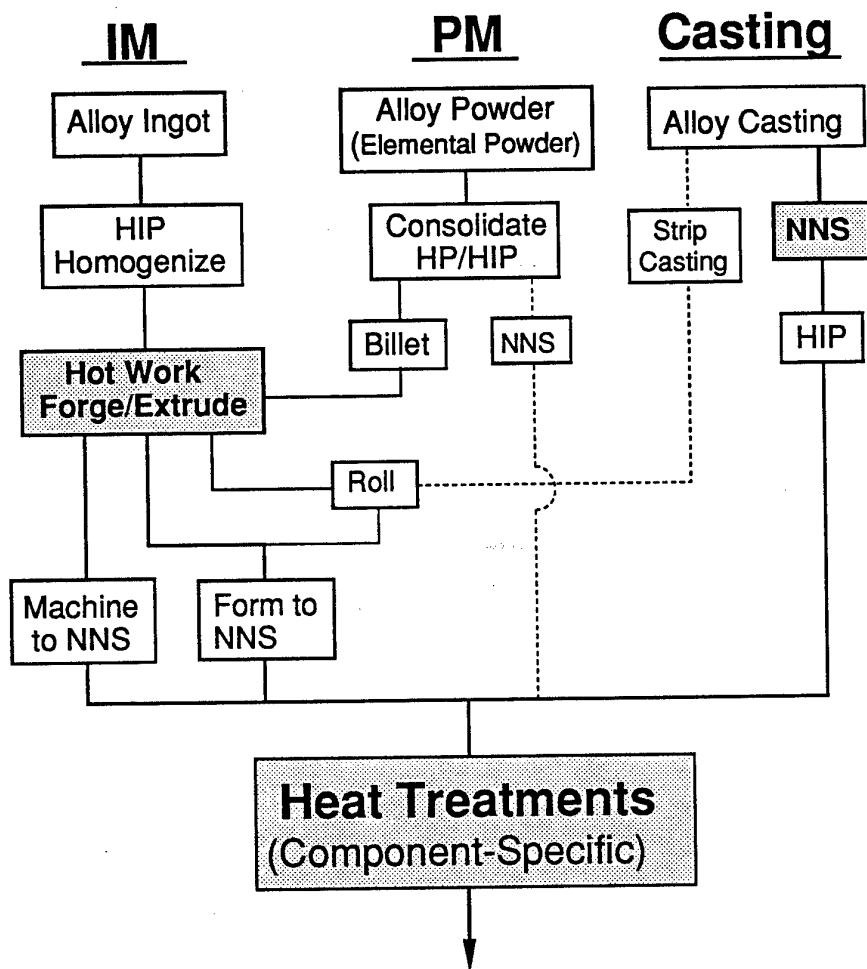
Ti-51Al-1.1 wt%Ox

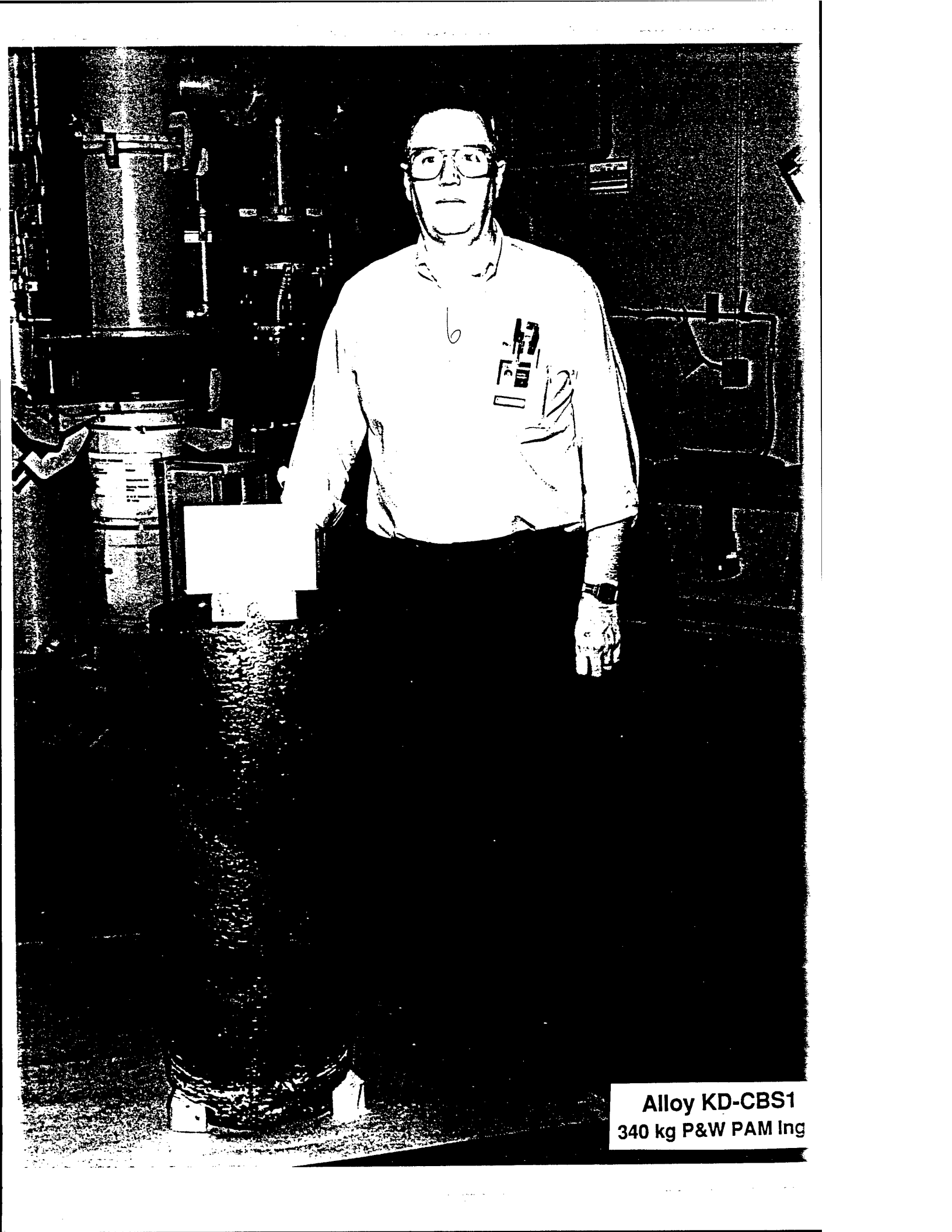
1350°C/6 hr/FC

CAST ALLOYS

Processing Routes for Gamma Alloys

16m (90-95)





Alloy KD-CBS1
340 kg P&W PAM Ing

Microstructural Evolution and Control

Principle

Phase Relation and Transformation

In Practice

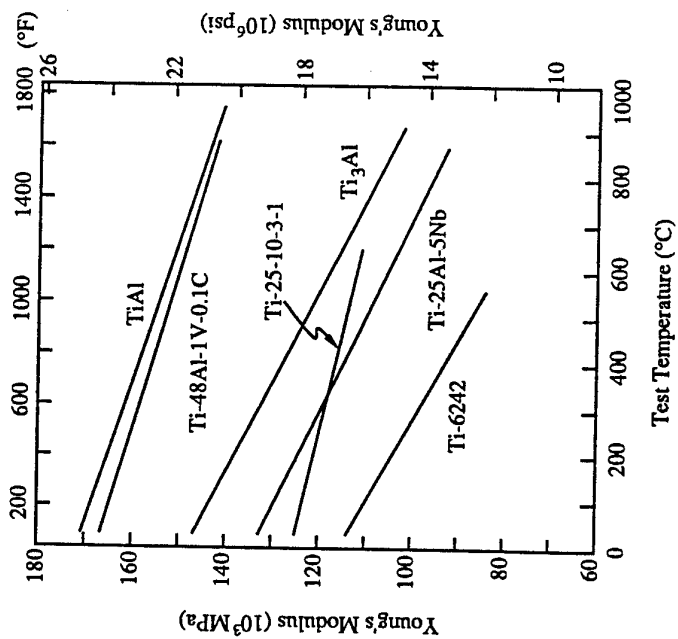
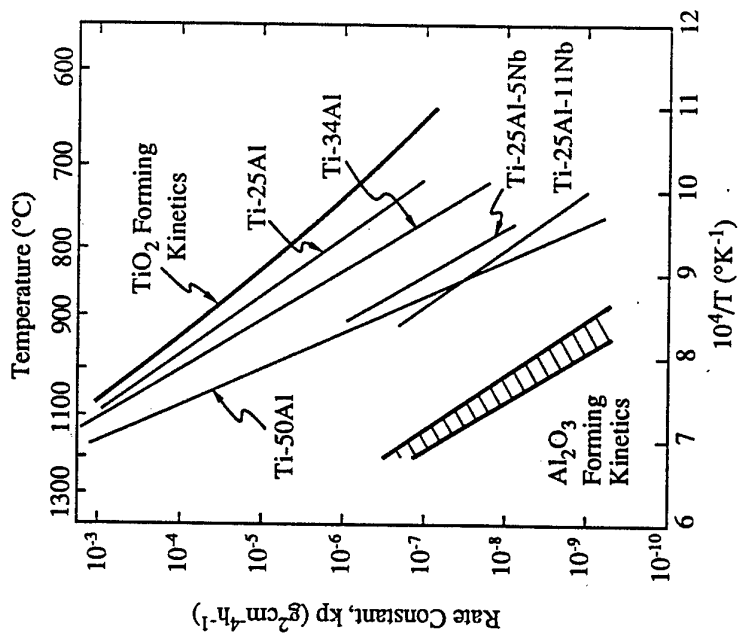
Formation/Growth Kinetics, Distribution and
Morphology Depend on Starting Microstructural
and Compositional Conditions.

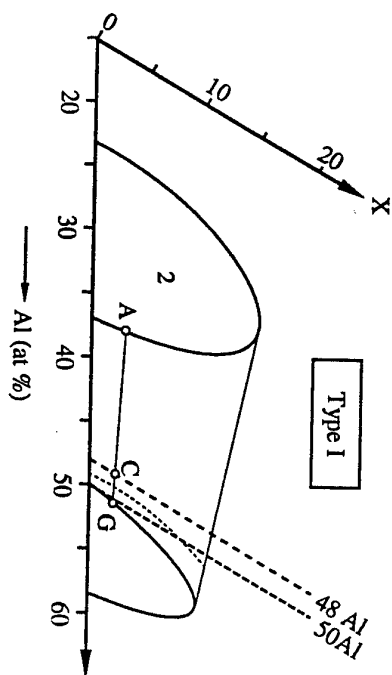
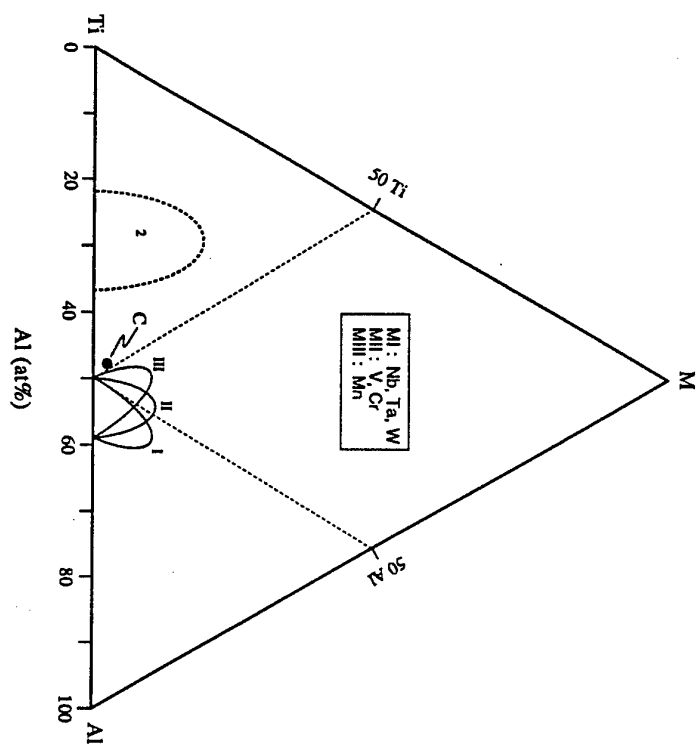
Controlling Factors

Temperature and Time
Heating Rate, Cooling Rate, and Scheme
Aging Method and Condition

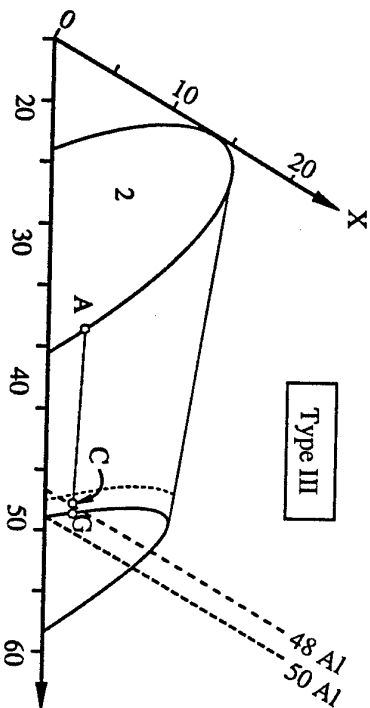
Starting Material

Cast Product
Ingot Wrought-Processed Material
PM Processed Material
Material Processed by Other Processes

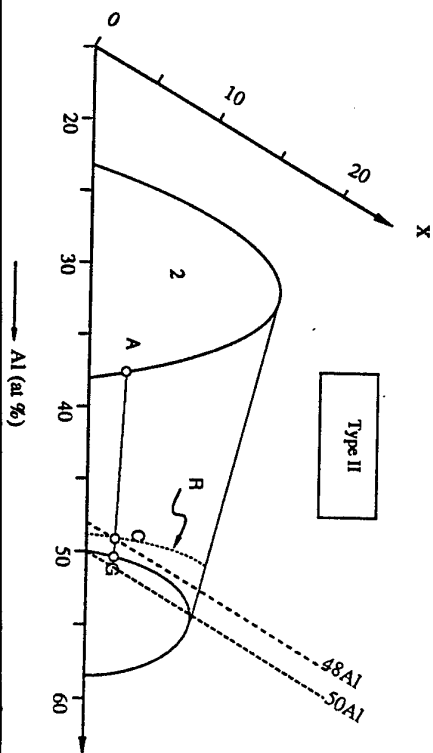




Type III



Type II



Processing

Ingot Preparation

Methods: ISM; PAM; VAR; VAR-Skull

Size Limitations (?)

Compositional/Microstructural Issues

NNS Casting

Investment vs. Permanent-Mold

Issues: Refinement; Porosity/Hip-Cycle

Thin-Section Casting

Wrought Processing

Primary: Conversion; Mill Production

Secondary: Forming, Rolling, etc.

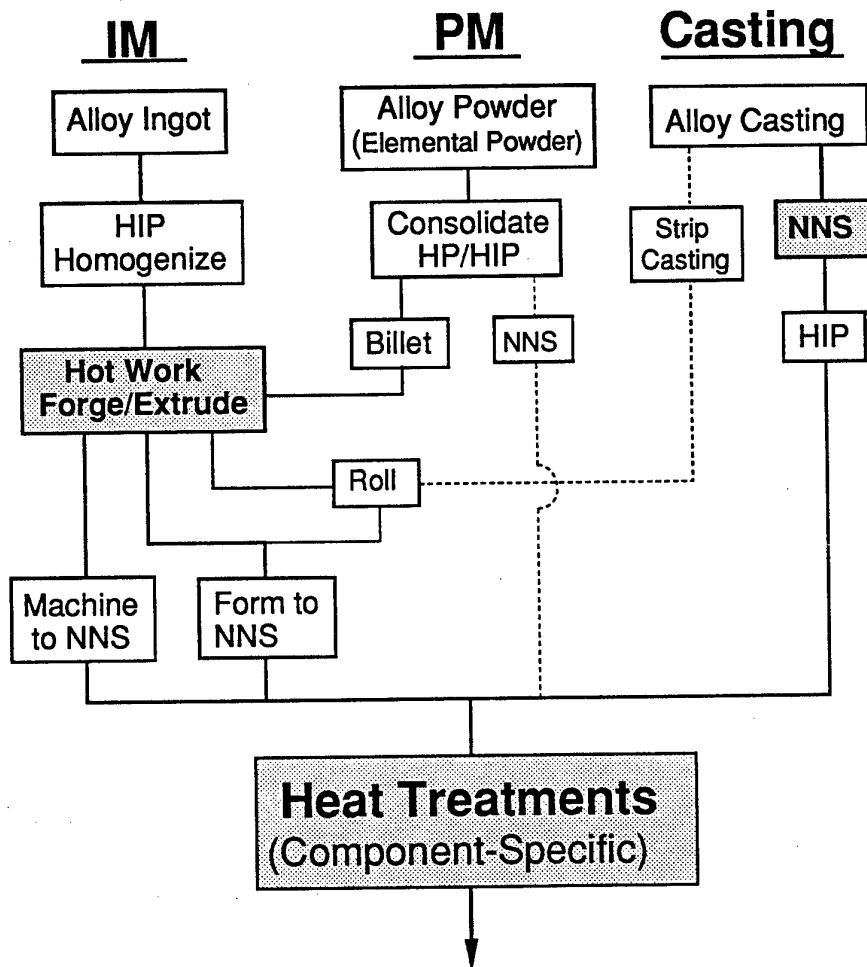
Heat-Treatment Cycles

Joining; Machining

Other Processes

Processing Routes for Gamma Alloys

Kim (90-95)



Microstructure Control in Castings

Standard Alloys

Ti-47Al-(1-2)Cr-(2-4)(Nb,Ta,W)-(0-0.2)Si

As-Cast Microstructures

Non-uniform; Lamellar Base

Controlled Microstructures

Refining and Uniformization

Practical: Casting Duplex

Desired: NL; Refined FL

Boride-Containing Alloys

XD Gamma Alloys

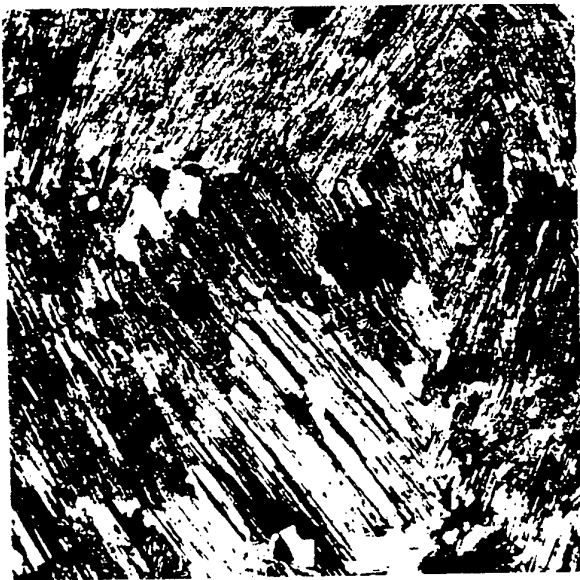
Ti-(45, 47)Al-4(Cr,Mn)-2Nb-0.8TiB₂

TMT-Type Microstructures

Others: IHI; GKSS

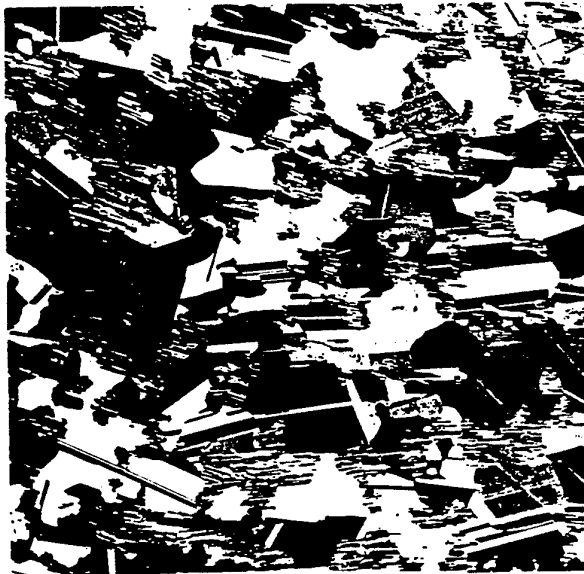
Inoculation by Borides

Microstructures in Castings

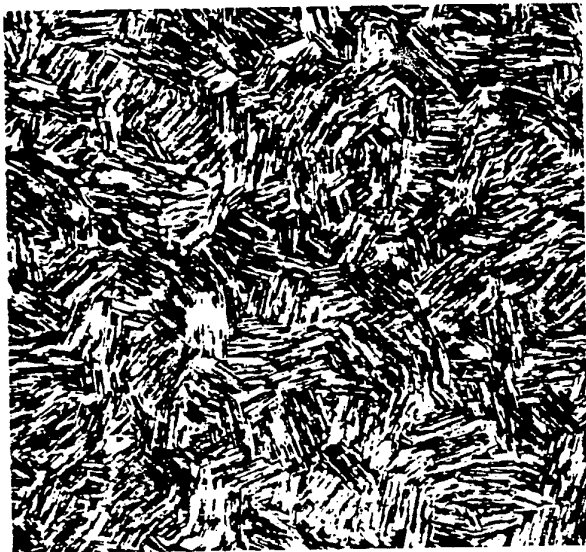


Cast and HIP'ed

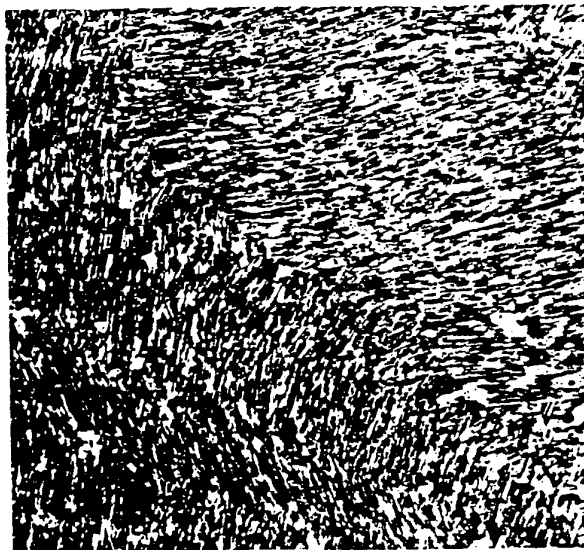
200 μm



Casting Duplex



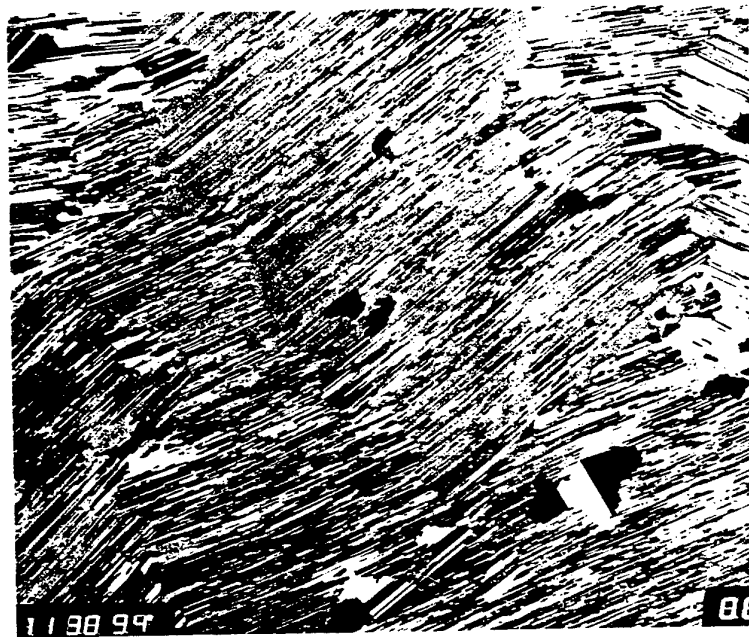
XD (HIP'ed)



GKSS, As Cast

Casting RFL

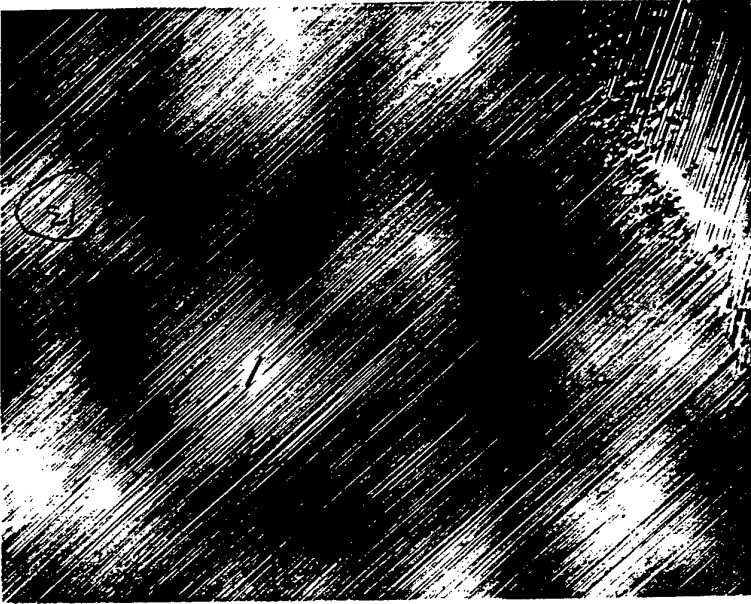
As-Cast



T α - Δ T Treated



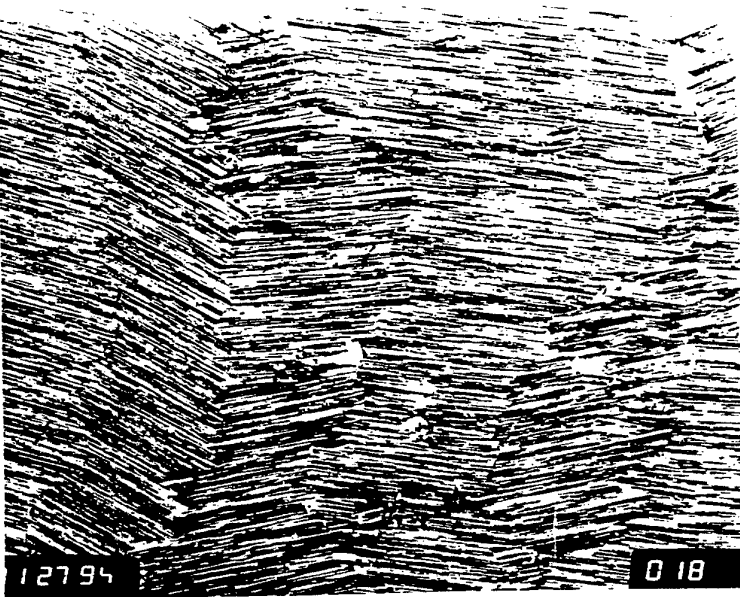
~~Not a true photograph~~
 ①: ~~Handwritten notes~~



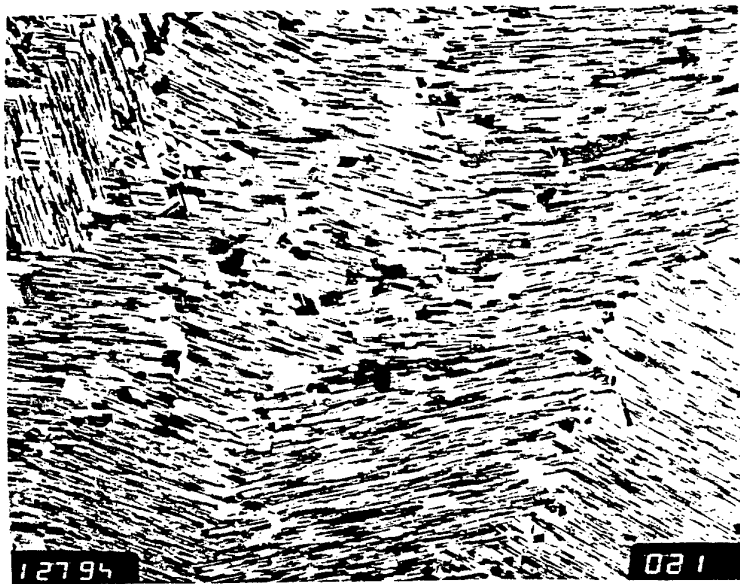
309-09: 1440/28 200X



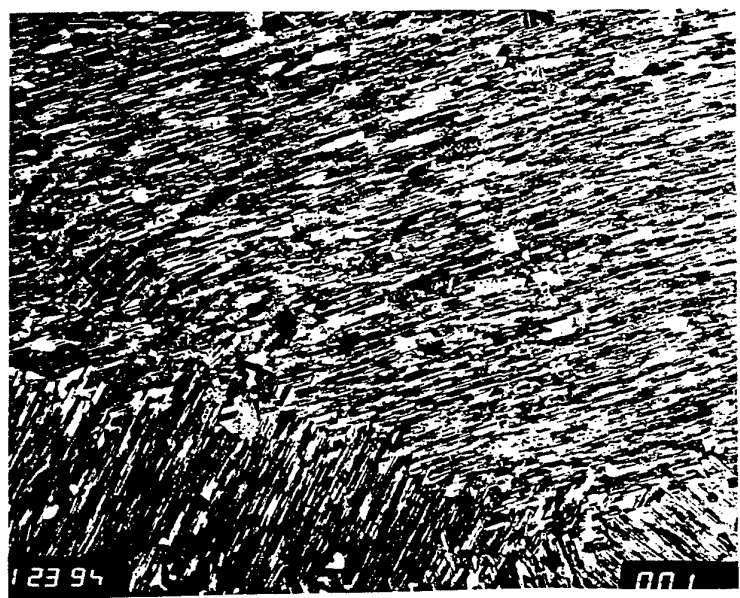
309-1A: 1320/28 200X



GKSS-2 1350/40m/FC/1000 100x PL

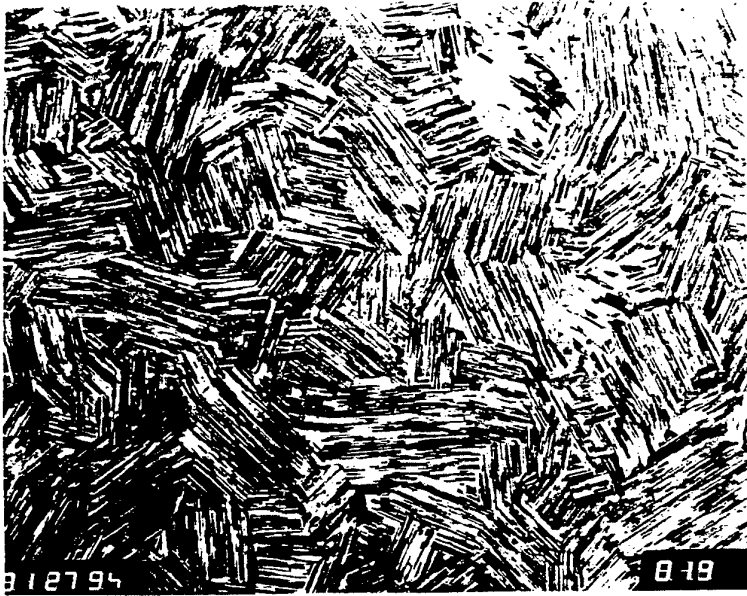


GKSS-3 1320/2H/FC/1000 100x PL

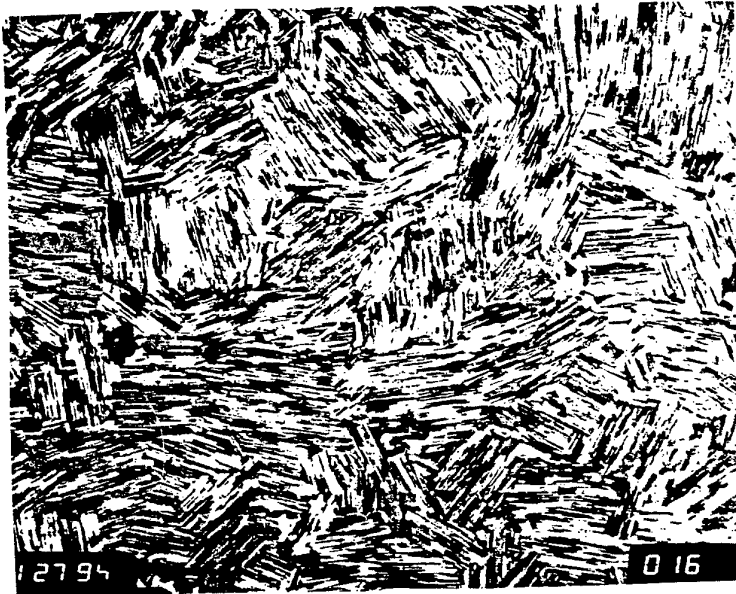


GKSS 100x As Received. P.L.

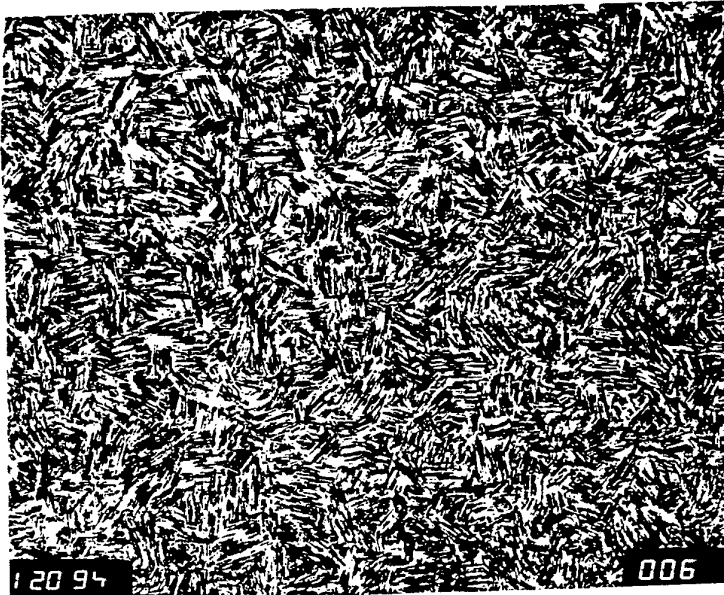




XD01-2 1370°/40 min / FC/1000 100x P.L.



XD01-3 1320°/2Hr / FC/1000 100x P.L.



XD-01 50x Cast

Microstructure Control in Wrought Alloys

Standard Alloys

Ti-47Al-(0-3)(Cr,Mn,V)-(0-6)(Nb,Ta,Mo,W)

As-Processed Microstructures

Fine Mixture of Gamma and Alpha-2

Heat Treatments Yield

Standard Microstructures

Standard Microstructures

Types

Near-Gamma (NG)

Duplex (DP)

Nearly-Lamellar (NL)

Fully-Lamellar (FL)

Inverse EI/K1c Relationship

Difficulties in Designing

Effort on Fundamental Understanding

Designed Microstructures



1300°C/1 HR/00 + 900°C/1 HR/AC

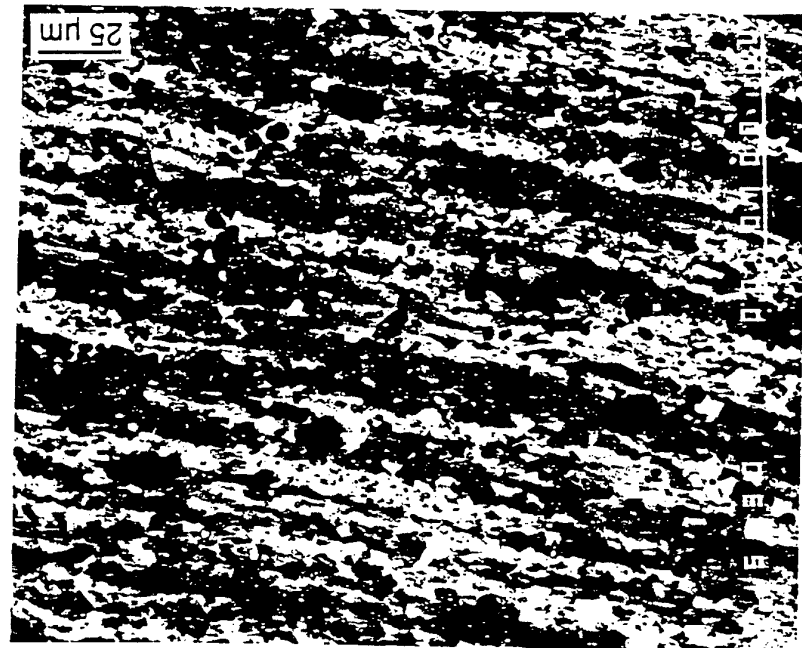


1380°C/2 HR/CC + 1180°C/30 MIN/AC

TI-46AL ALLOY CIGAR



K5 (Ti-46.2Al-2Cr-3Nb-0.2W)



K5WSB (K5+0.3W+0.2Si+0.1B)

Alloy K5's: Isothermally-Forged (1150°C/70/70)

50 μm



Ti - 47Al - $x_1\text{Si}$

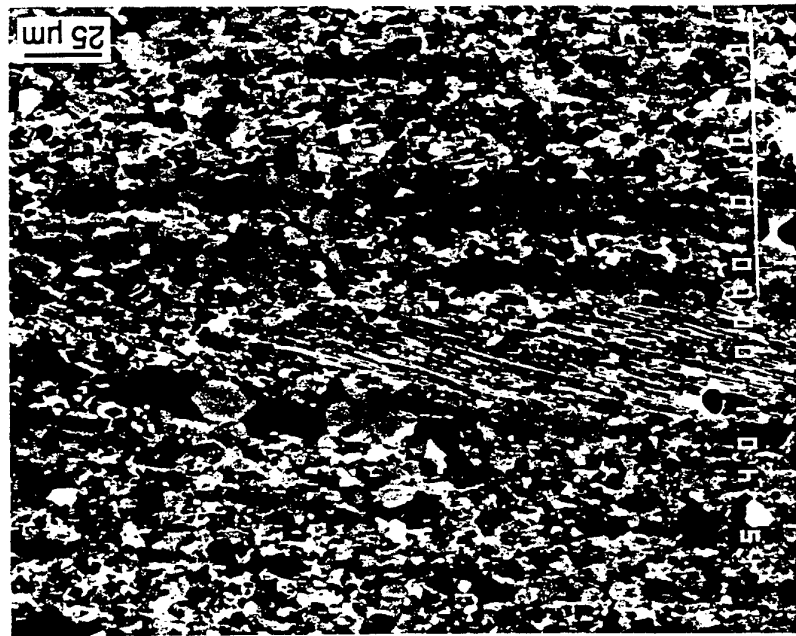


Ti - 47Al - $x_2\text{Si}$

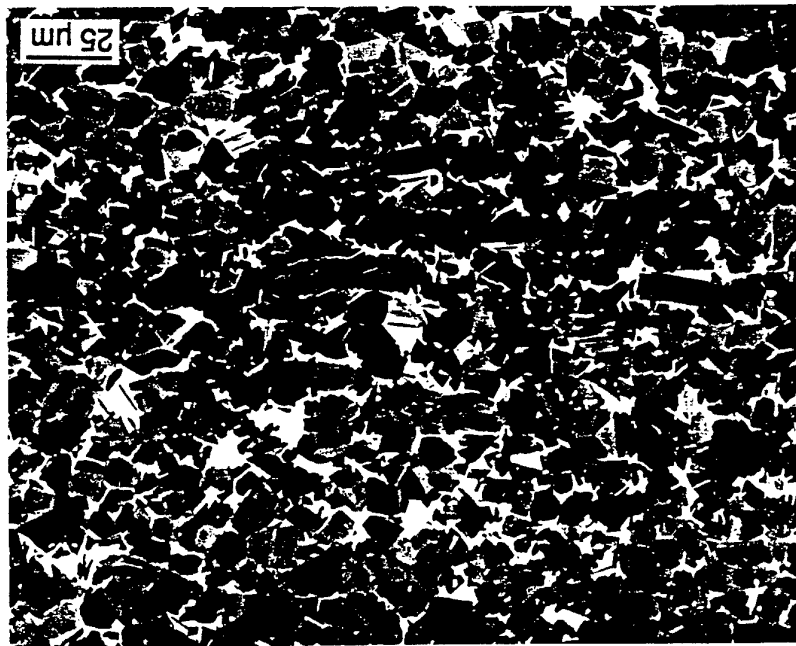


Ti - 48Al - $x_2\text{Si}$

Isothermally forged(85%) microstructures



1150°C/70/70



1270°C/3h/FC

Alloy K5: Isothermally-Forged and Duplex-Treated

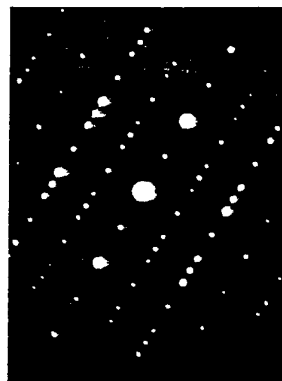


T α -70°C / 4hr / AC

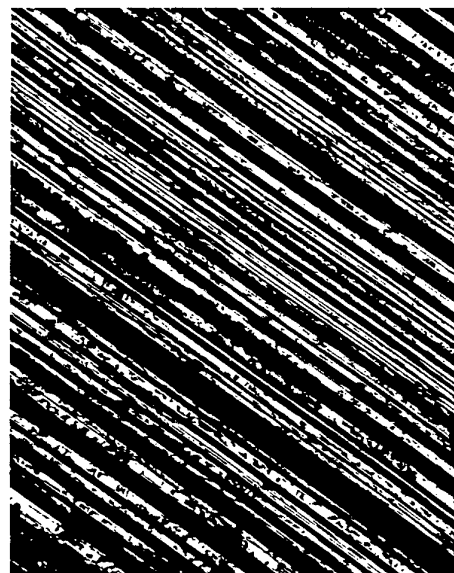


T α -70°C / 24 hr / AC

10 μ m



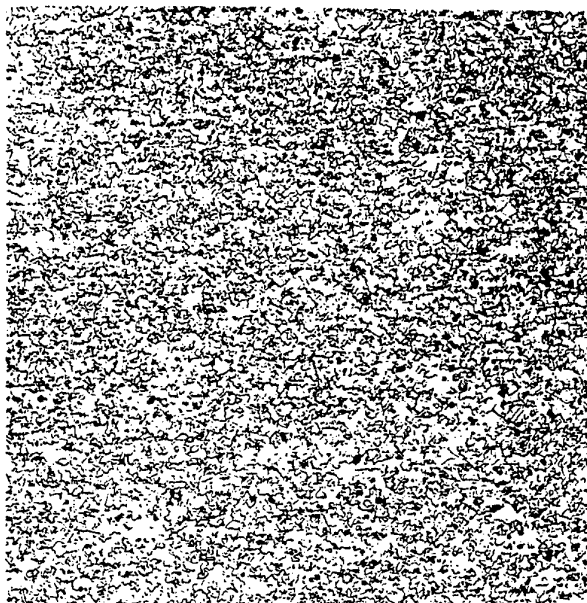
1 μ m



Lamellar Structures : Light-to-Gray Areas

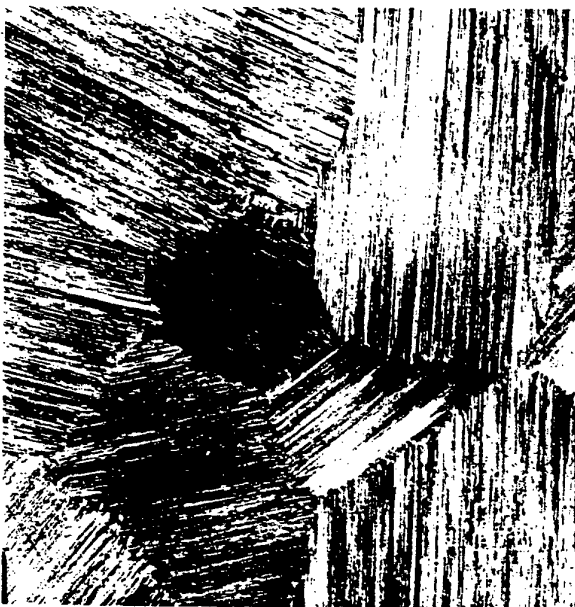
Alloy G1 : Forged + (α + γ) Treated + Air Cooled

Microstructures of Gamma Alloys

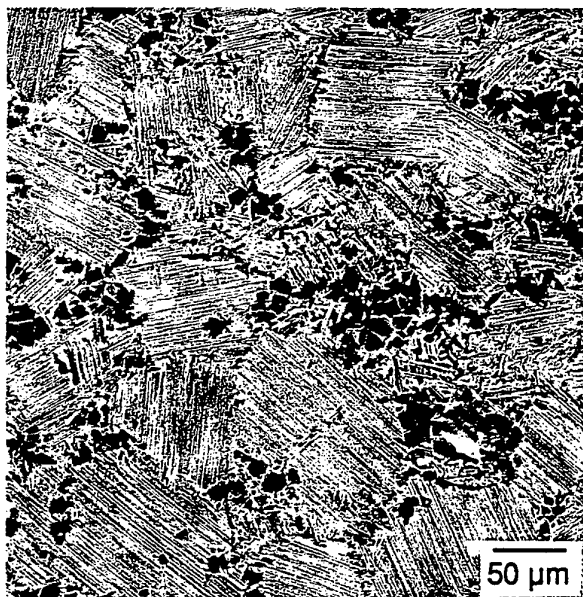


Duplex

200 μm

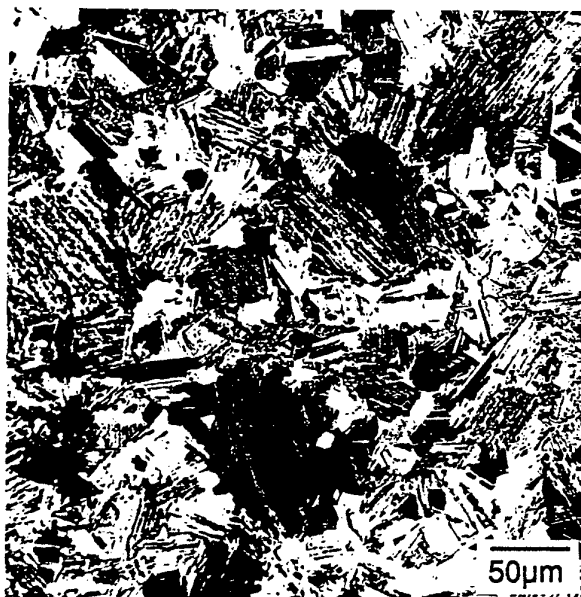


Fully-Lamellar (FL)



Nearly-Lamellar (NL)

50 μm

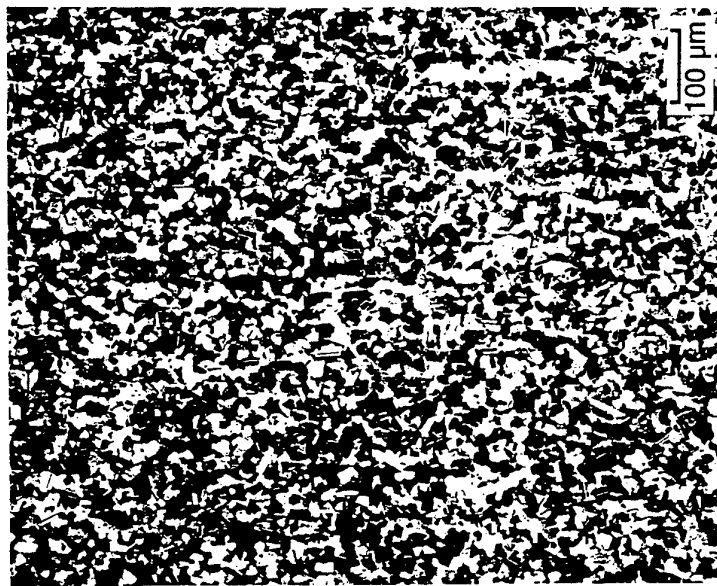


NL

50 μm

Alloy K5 (Ti-46.5Al-2Cr-3Nb-0.2W)

Duplex

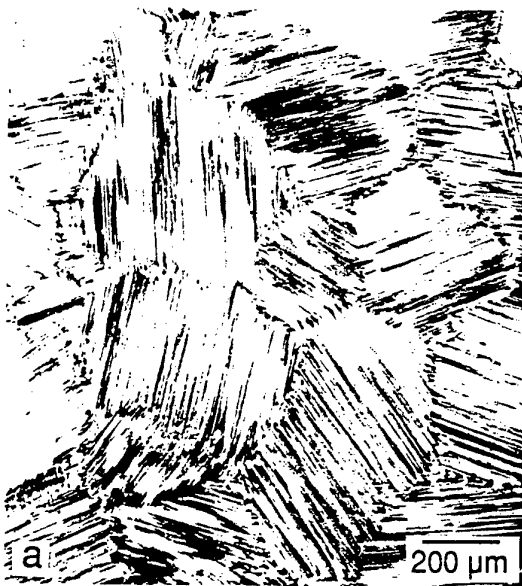
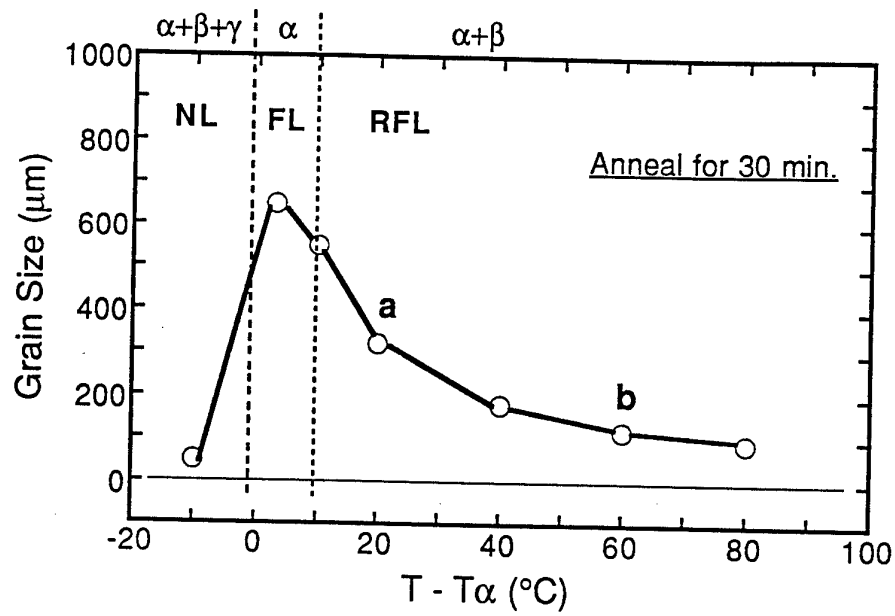


HW + (α + γ)-Treated

Fully-Lamellar



HW + α -Treated



Lamellar Grain Size Control in Wrought Alloy K5



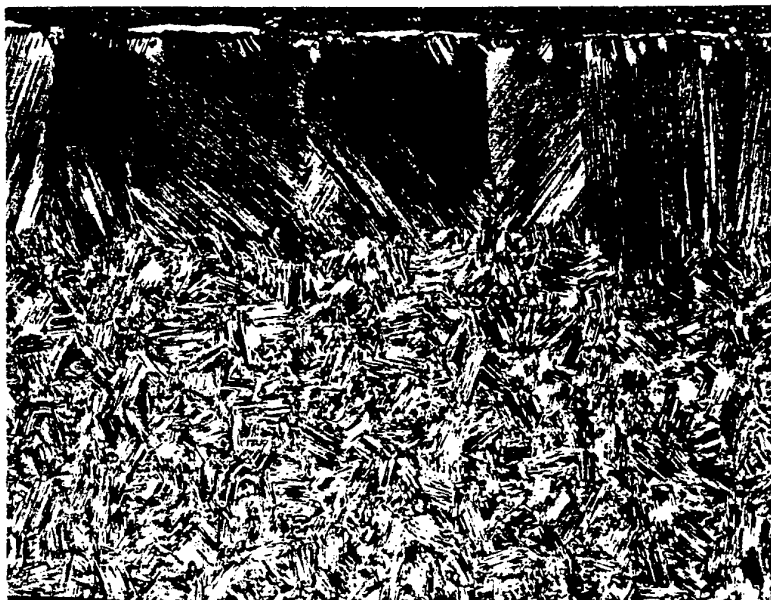
Cooling Condition Effect on RFL of Alloy K5

Alloy 13: Ti-46.4Al-2.1Cr-3Nb-0.2W

200 μ m



K5L-19

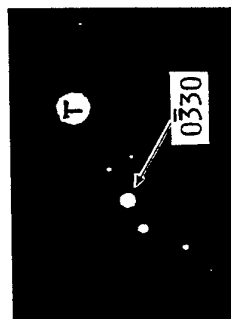
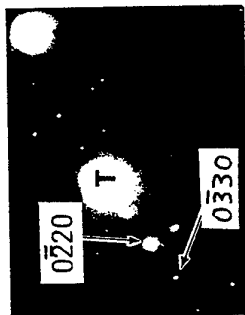


K5L-12

Wrought Alloy K5 after High Temperature Treatments



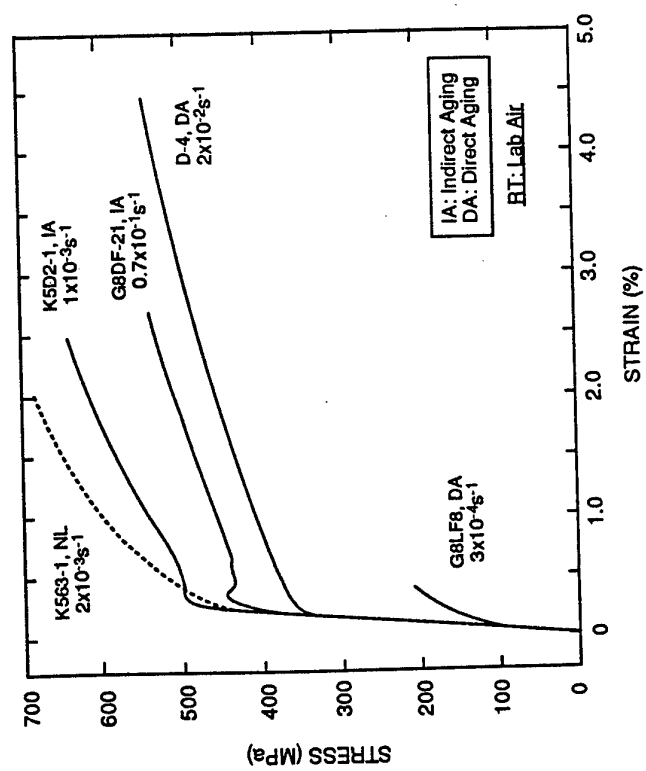
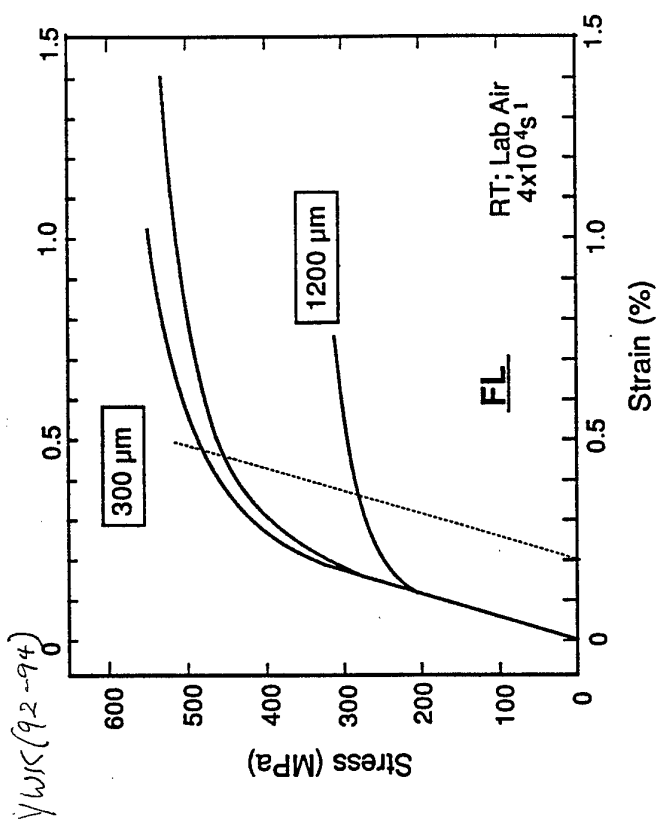
1 μ m



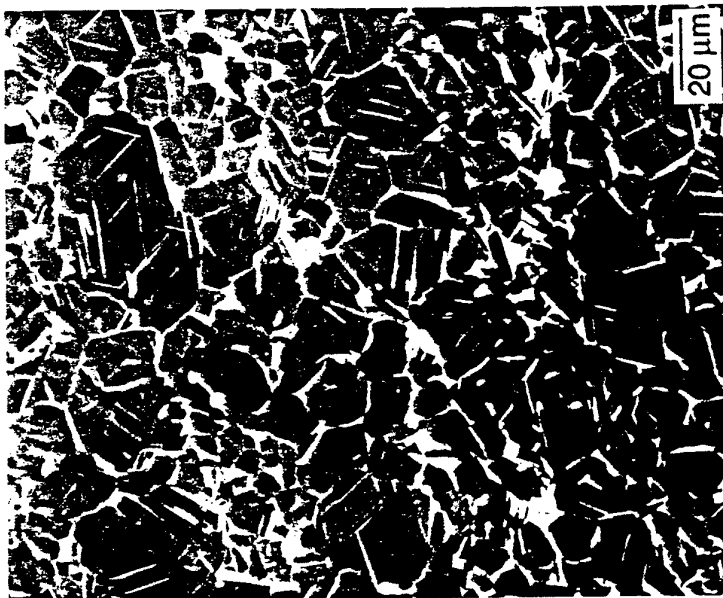
$[2\bar{1}10]//[110]$



ALLOY G16 FORGED (88%) AND HEAT TREATED (1200°C/2 HR/AC + 1000°C/24 HR/AC)



RT Tensile Curves in Duplex/NL Microstructures

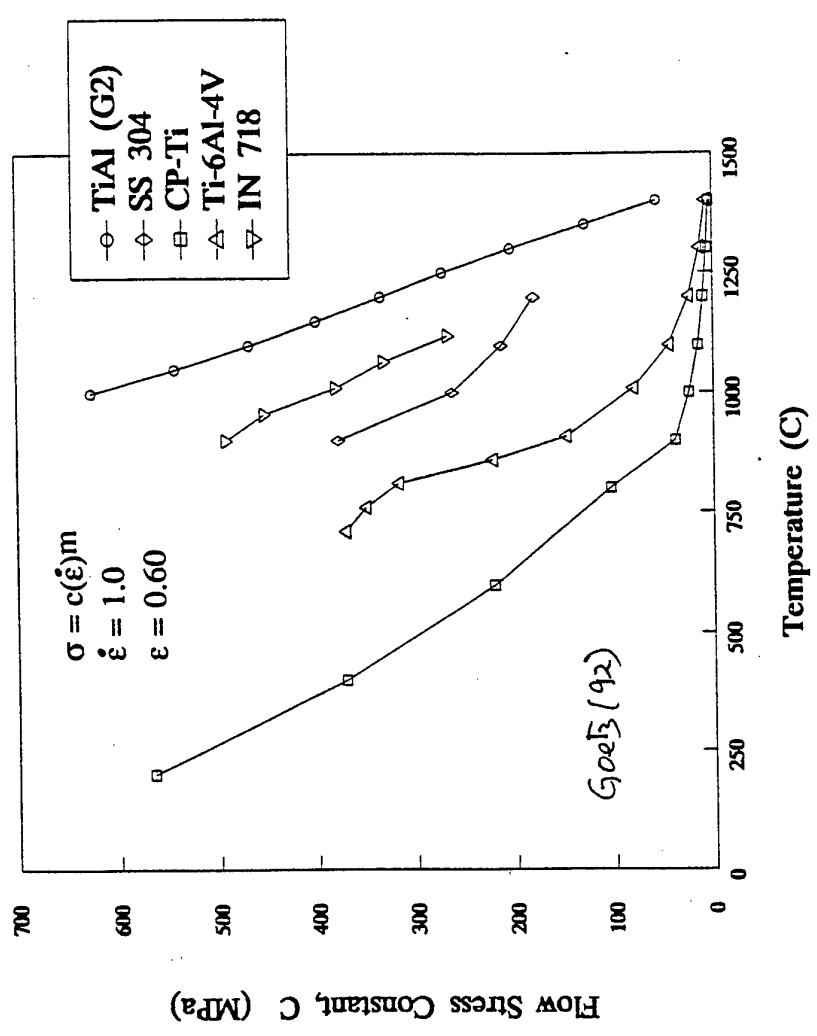
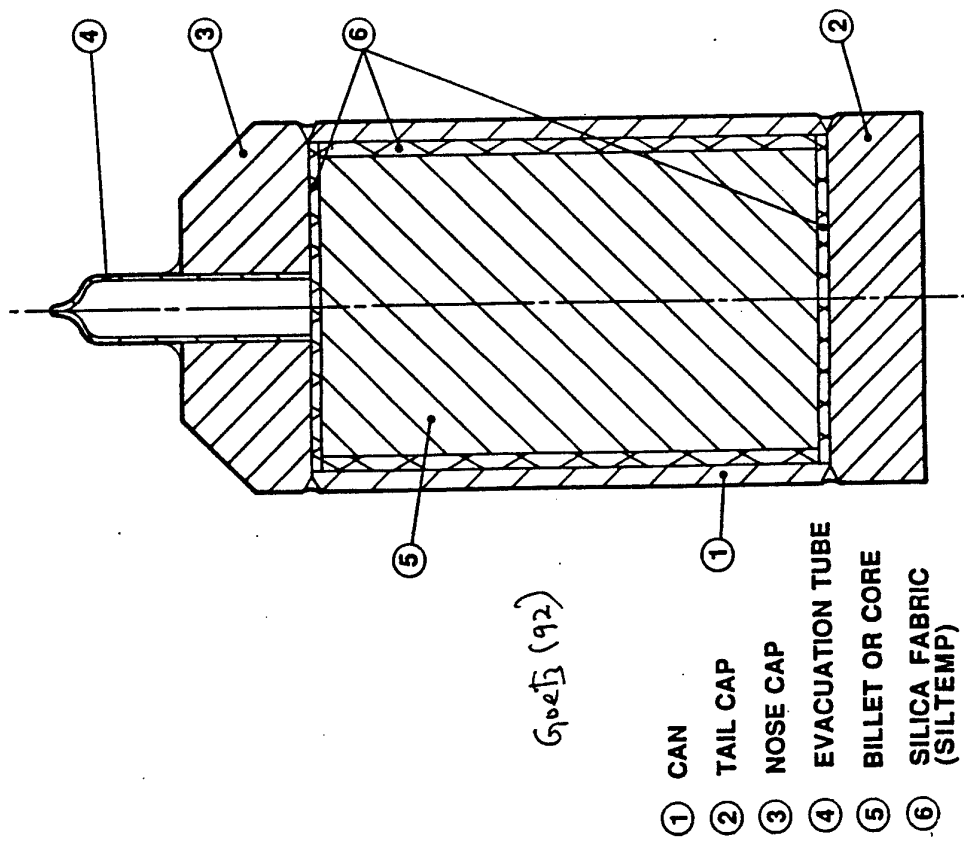


Directly Aged



Indirectly Aged

Duplex Microstructures in Alloy G1



Structure/Property Relationships

General Mechanical Behavior

- Tensile
- Fracture Toughness
- Creep
- Fatigue; FCG,

Inverse Ductility/FT Relationship

Deformation and Fracture Behavior

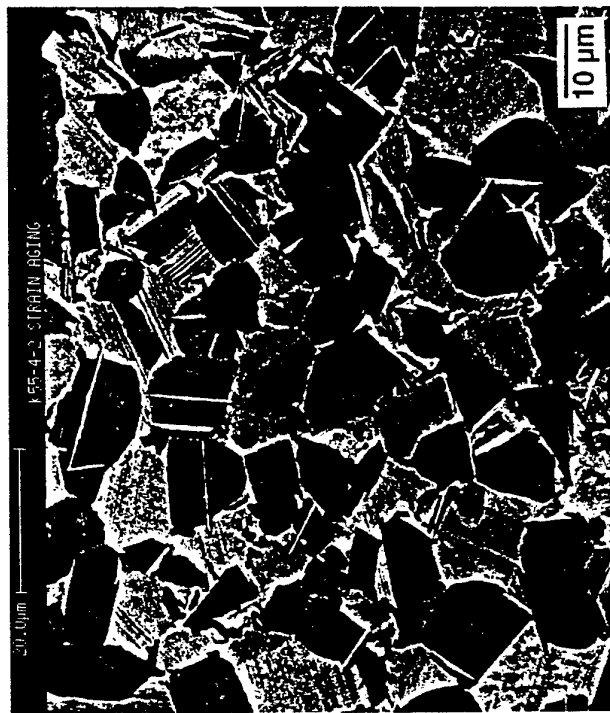
- Tensile Loading
- Cyclic Loading
- Creep Loading

Damage Tolerance and Life Prediction

Microstructure Optimization

Alloy K5 Duplex

1270°C/4h/AC/RT



Weak Yield Point

1270°C/4h/FC/900°C/AC
+ 900°C/48h/AC



Pronounced Yield Point

K5 Duplex: $\epsilon_t=0.5\%$

Weak Yield Point



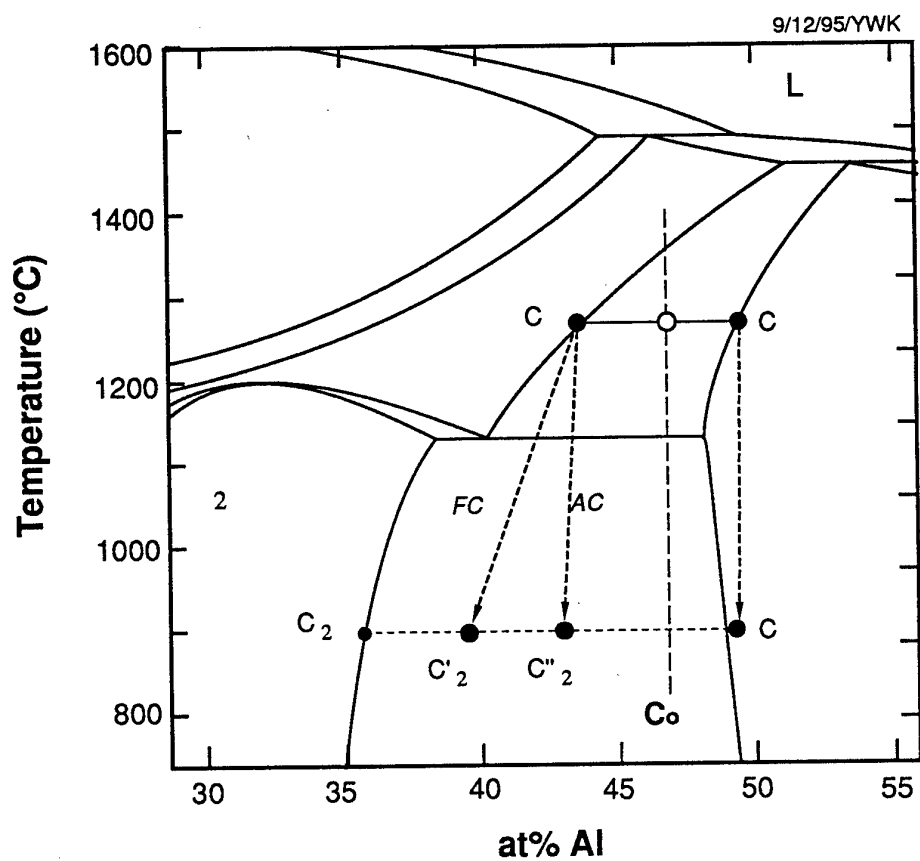
1270°C/4h/AC/RT

Strong Yield Point



1270°C/4h/FC/900°C/AC + 900°C/48h/AC

Duplex (+) Treatment and Cooling





Near Gamma



a Duplex with direct aging

10 μ m

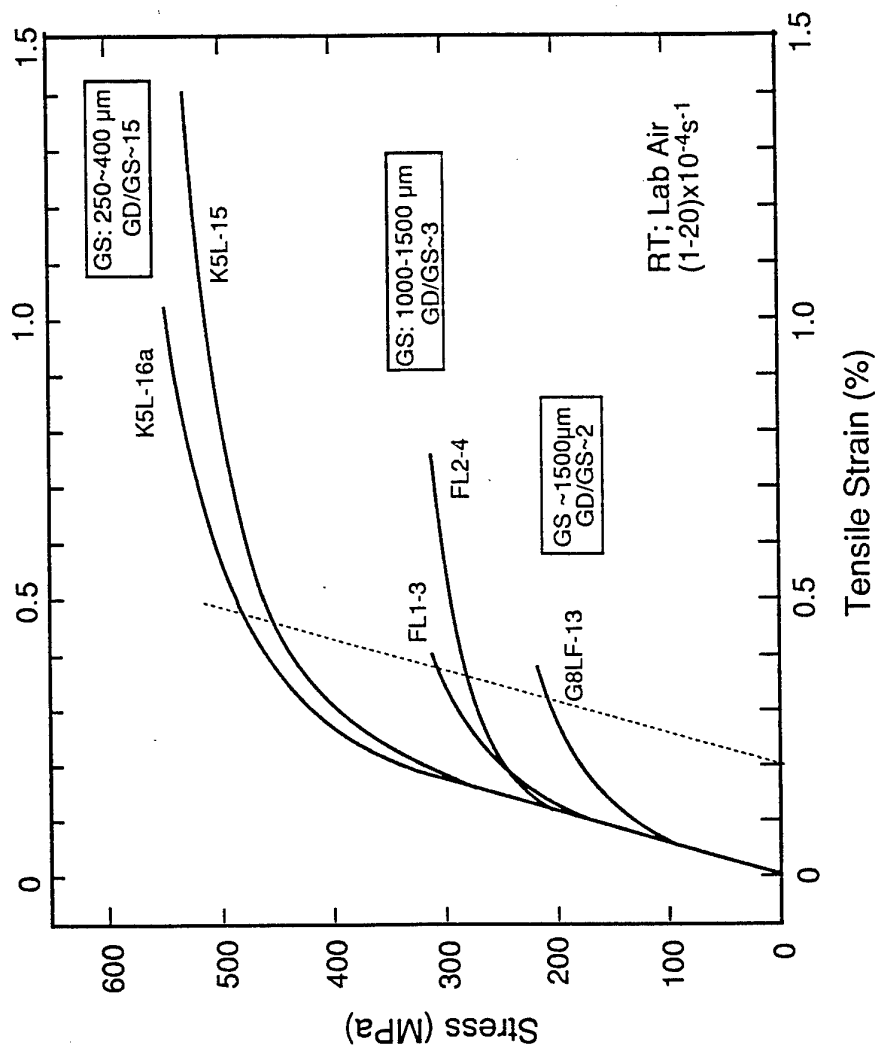


a Duplex with indirect aging

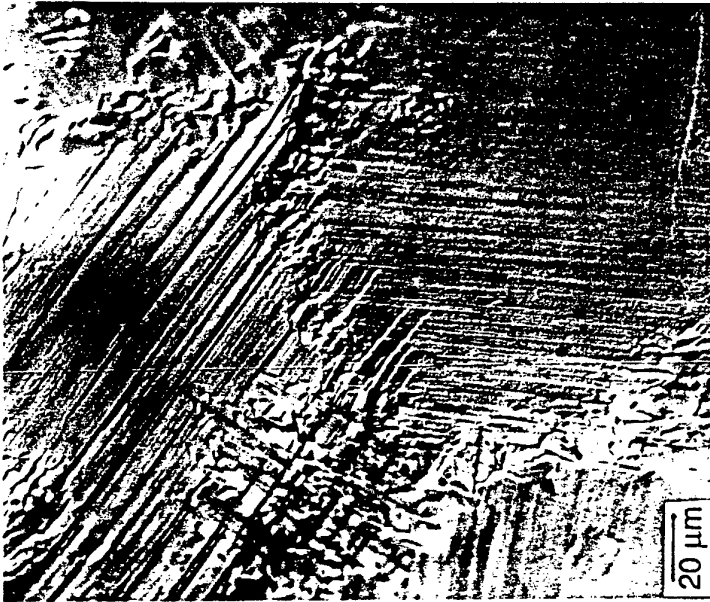


A Nearly-Lamellar with indirect aging

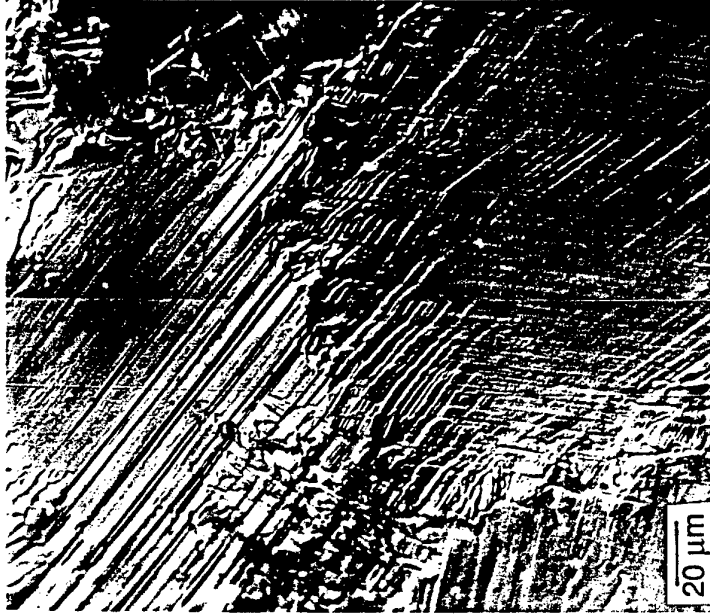
Tensile Fracture Surfaces of Alloy G1 in Various Microstructural Conditions



Tensile Curves of Fully-Lamellar Gamma Materials

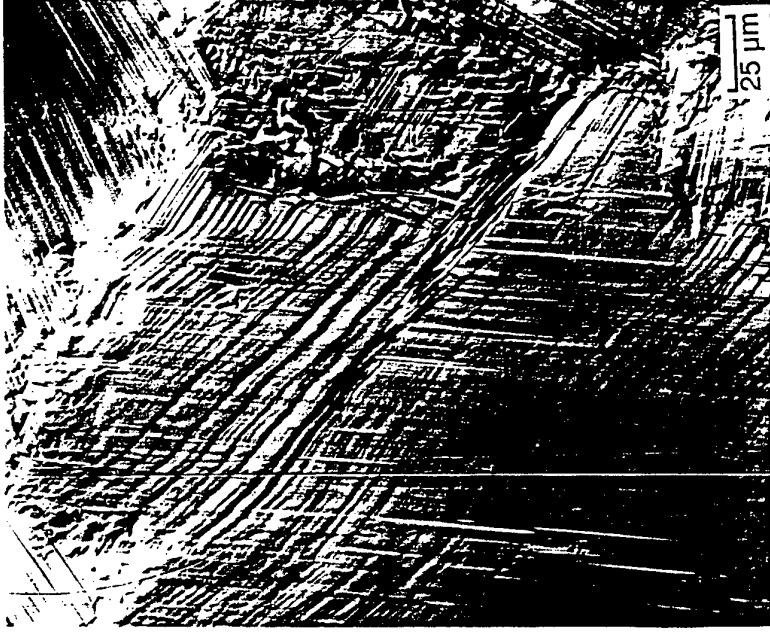
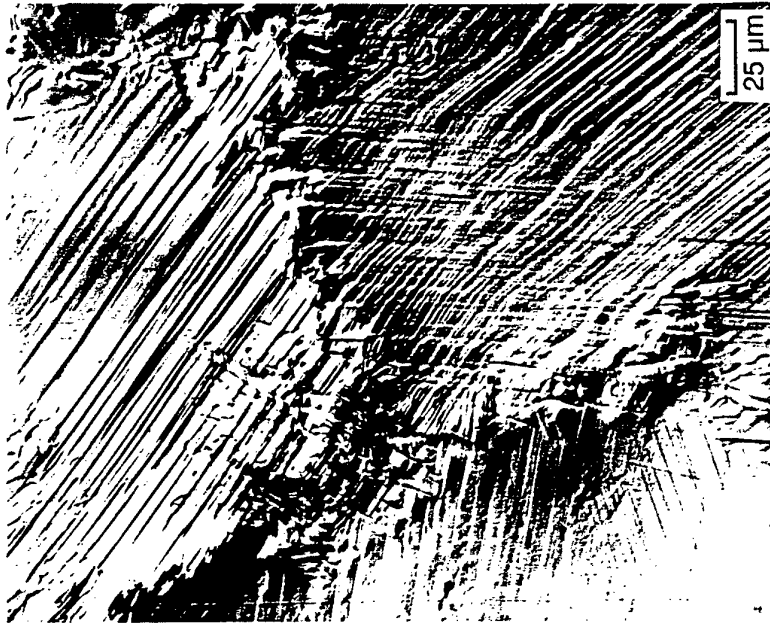


$\epsilon_1/\sigma_1 = 0.3 \text{ \%} / 427 \text{ MPa}$

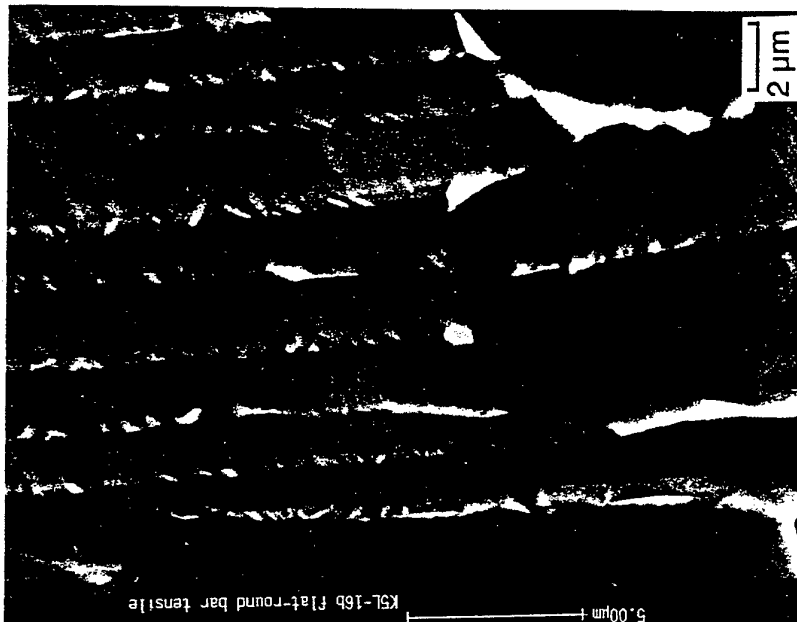
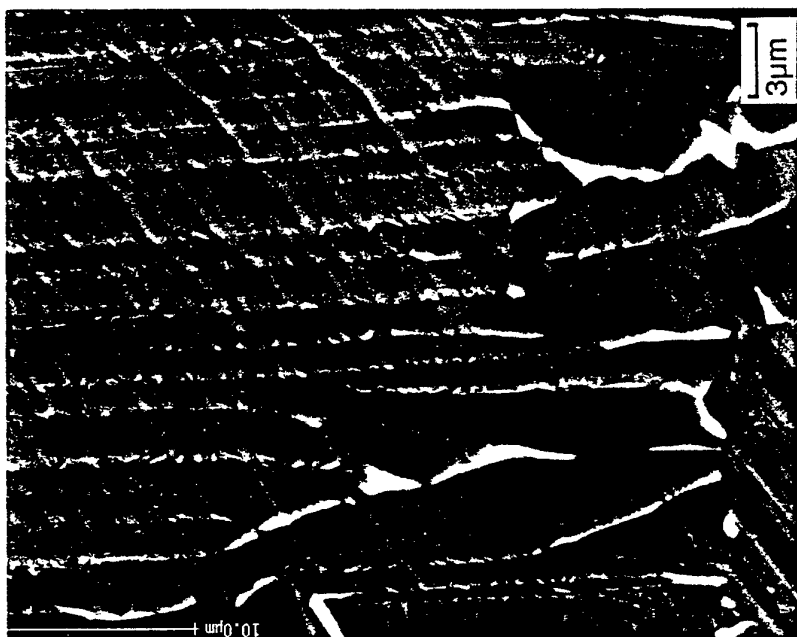


$\epsilon_3/\sigma_3 = 0.55 \text{ \%} / 493 \text{ MPa}$

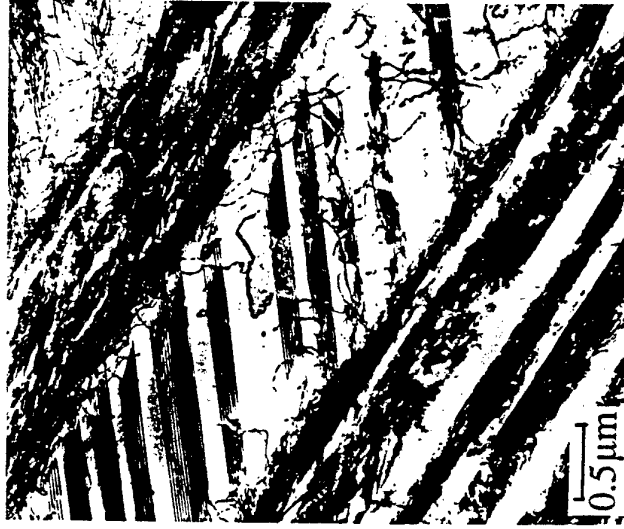
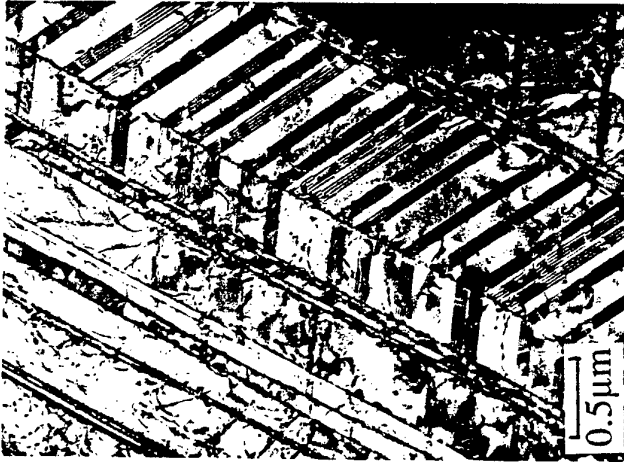
Alloy K5 RFL Flat Gage Tensile Specimen Surface Deformed at RT
 ($\sigma_o/\sigma_y = 328/474 \text{ MPa}$; $\lambda_L = 0.3 \text{ μm}$)



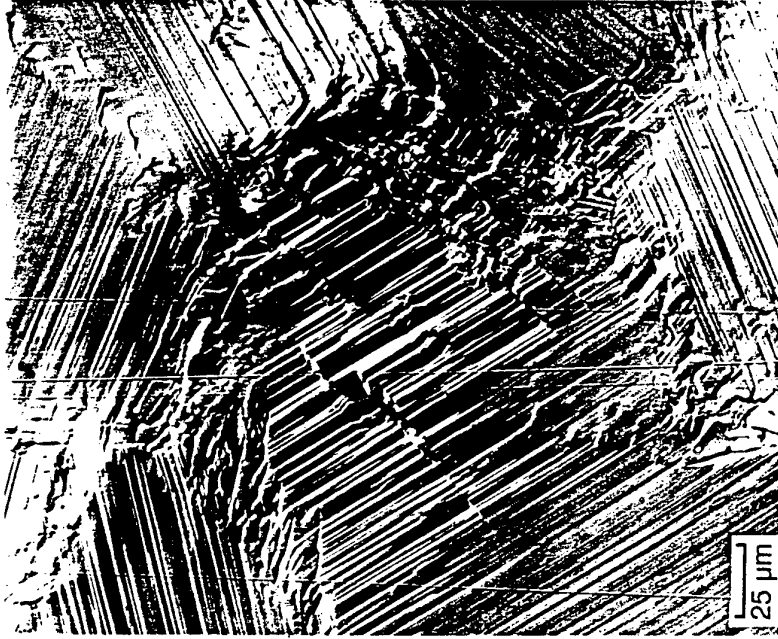
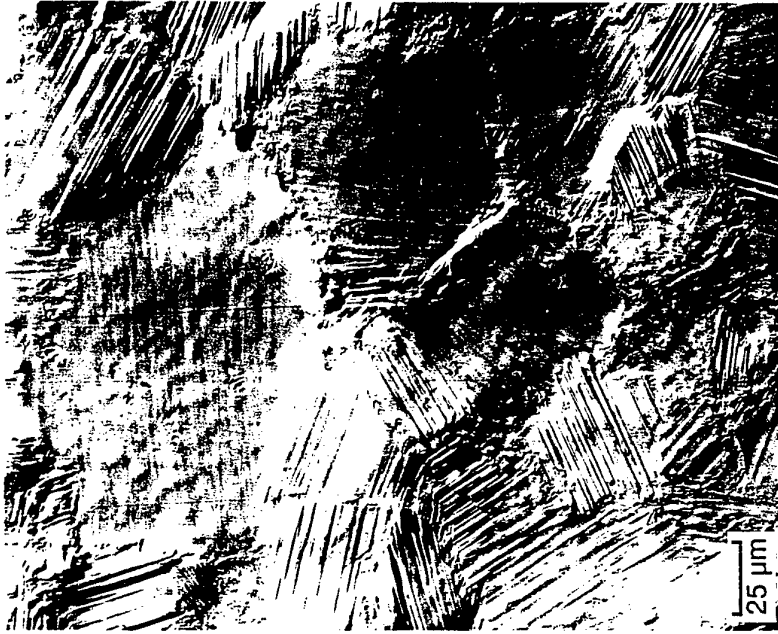
RT Tensile Deformation/Strain-Accommodation Observed on Electropolished Surfaces of Alloy K5 RFL Specimens at $\sigma/\epsilon=528$ MPa/1.21% ($\sigma_0/\epsilon_0=328/0.19$)



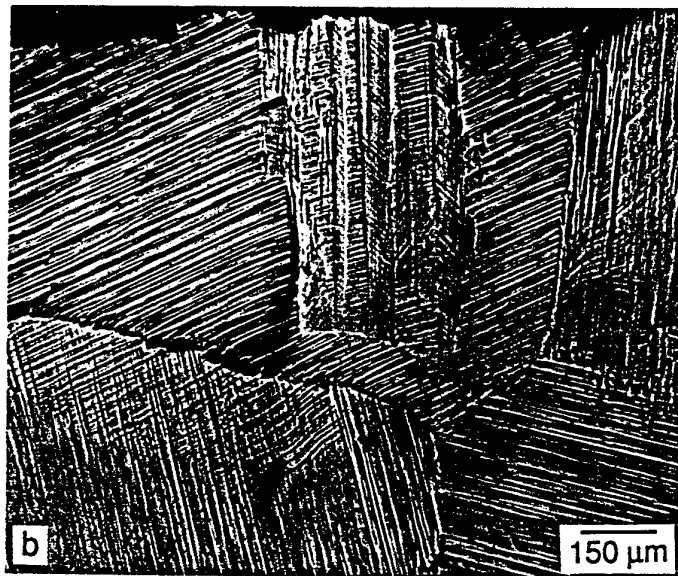
BSE Image of RT Tensile Deformation/Strain-Accommodation near GB's
on Surfaces of Alloy K5 RFL Specimens at $\sigma/\epsilon=528$ MPa/1.21% ($\epsilon_0=0.19$)

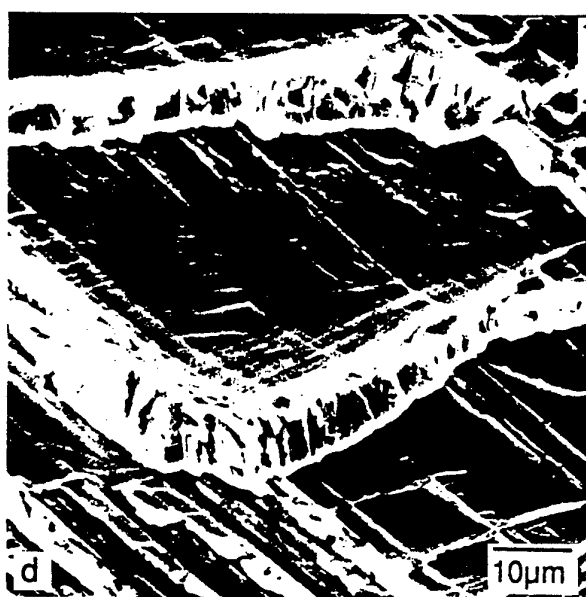
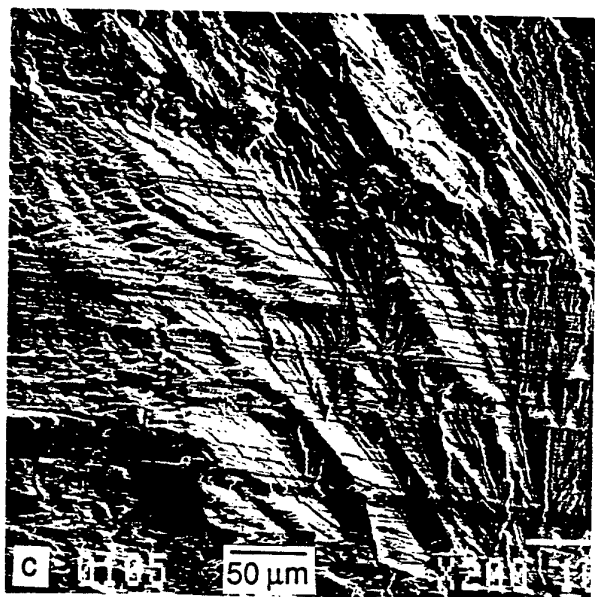
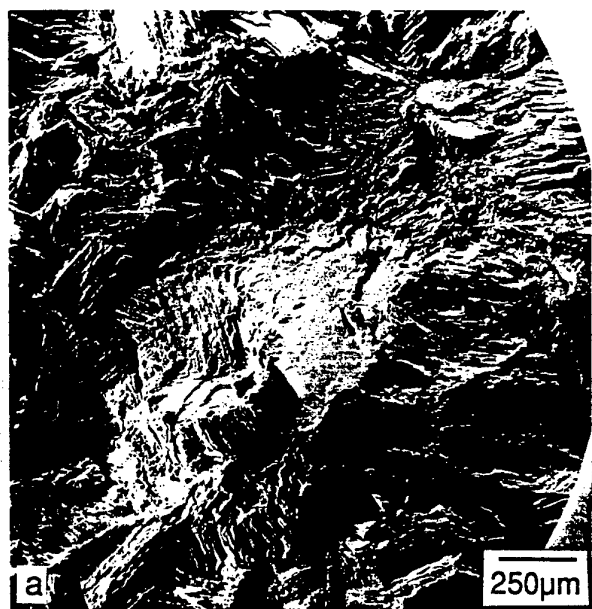


Deformed Microstructure of Alloy G1 at 1.9% Tensile Strain

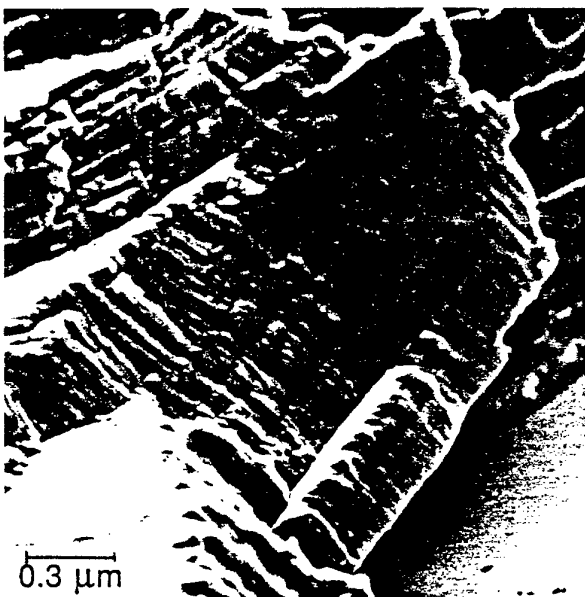
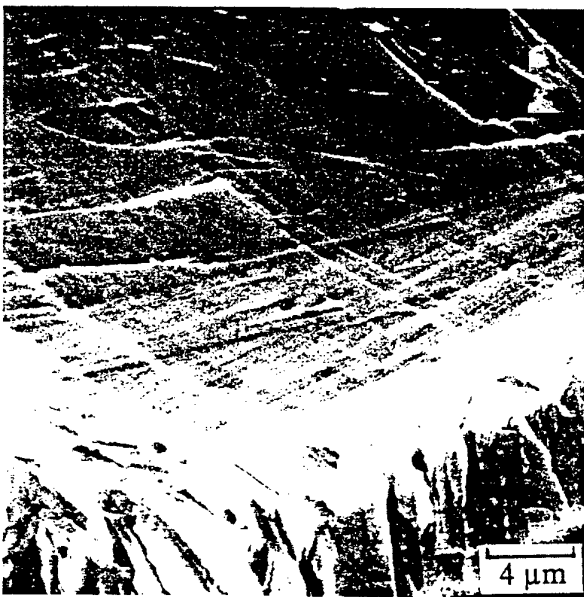
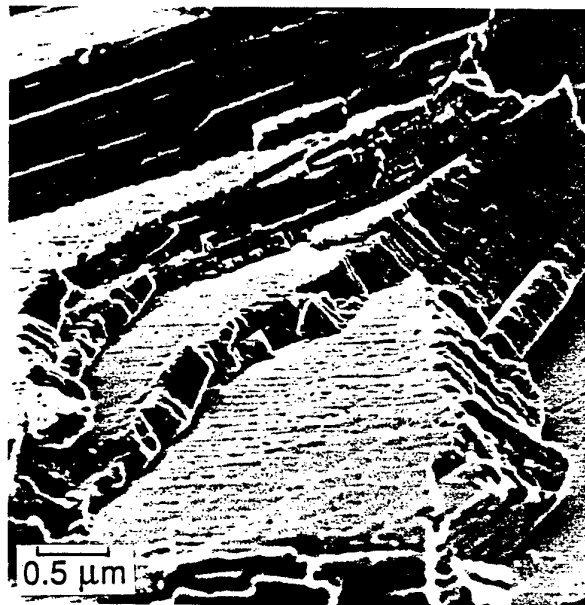
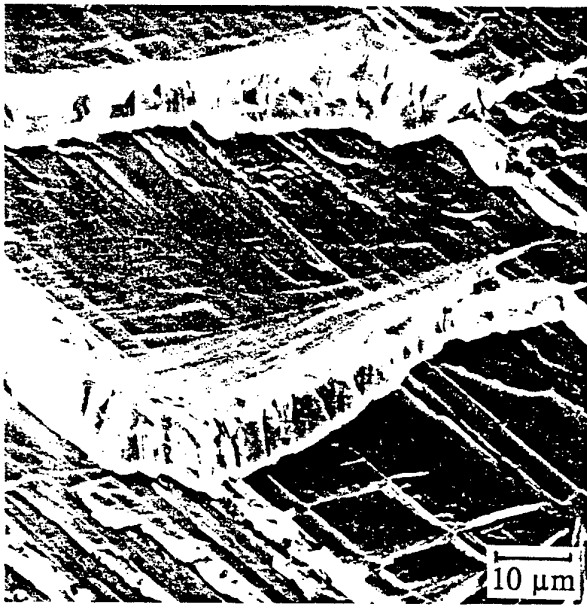


Alloy K5 RFL Tensile Specimen Flat Gage Surface Deformed at RT
 $\sigma_5/\epsilon_5 = 524 \text{ MPa}/0.78\%$ ($\sigma_0/\epsilon_0 = 328/0.19$)





RT Tensile Transgranular Fracture of FL Gamma Alloys:
 (a) Overall, (b) Interlamellar and Translamellar, (c, d)
 Translamellar Cleavage with Interlamellar Deformation

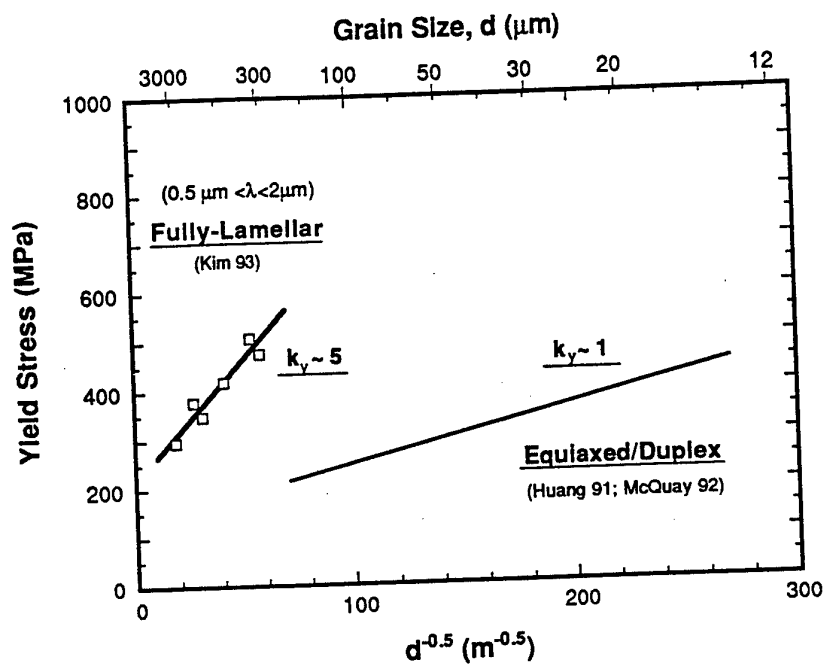


Fully-Lamellar

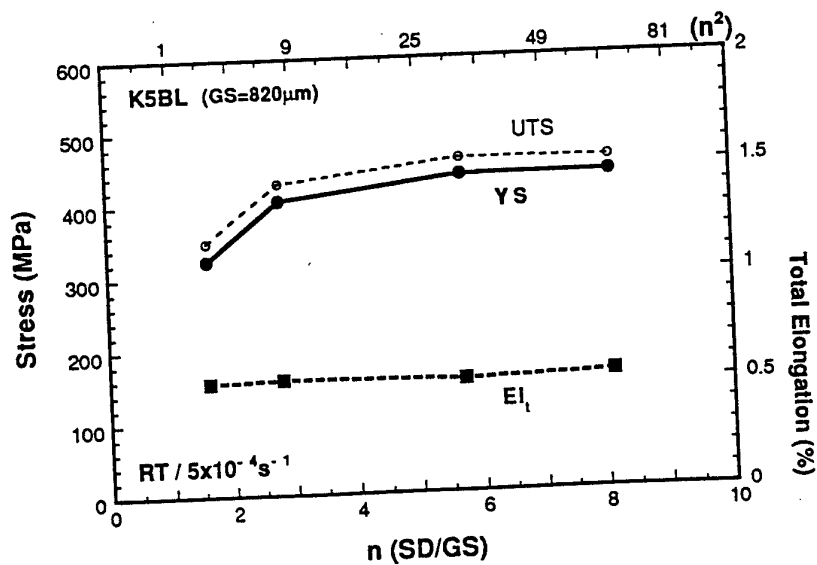
Duplex

RT Tensile Fracture Features of TiAl alloys in FL
and Duplex Microstructural Conditions

Grain-Size//Yield-Stress Relations in TiAl



Specimen/Grain Size Effect on Tensile Properties

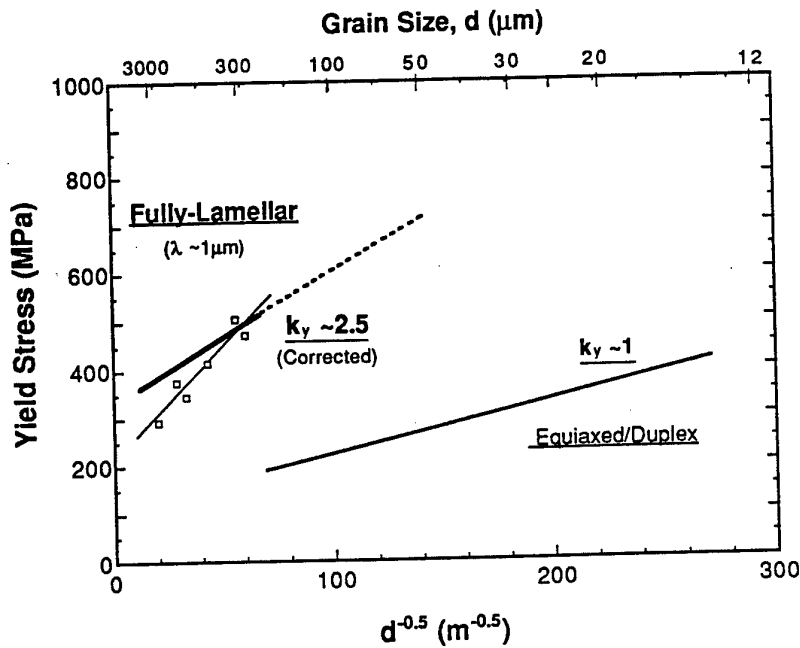




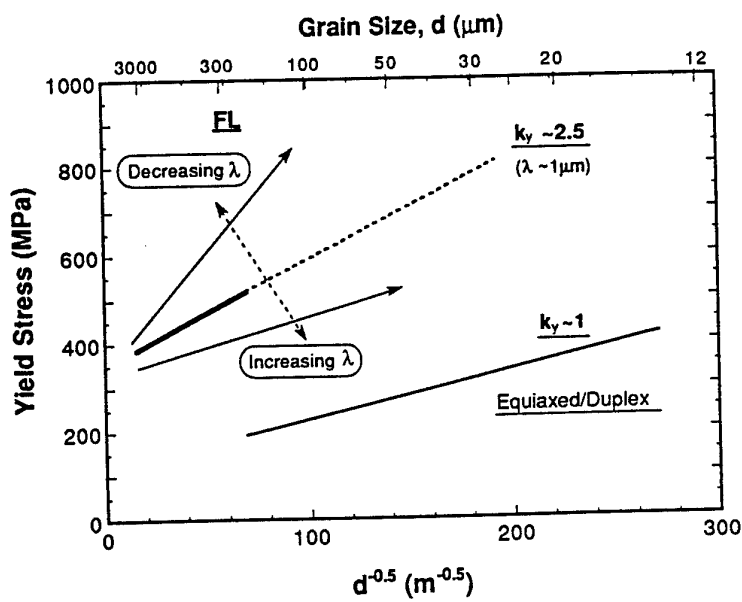
Specimen-Diameter/Grain-Size = 8.2:1

SD/GS=1.5:1

Corrected Hall-Petch Relation in FL TiAl



Hall-Petch Relations in TiAl Alloys



Hall-Petch Relations in TiAl Alloys

Duplex Material

$$\sigma_y = \sigma_o' = k_d d^{-1/2}$$

$$k_d \sim 1 \text{ MPa}\sqrt{\text{m}}$$

Relatively isotropic

Fully-Lamellar Material

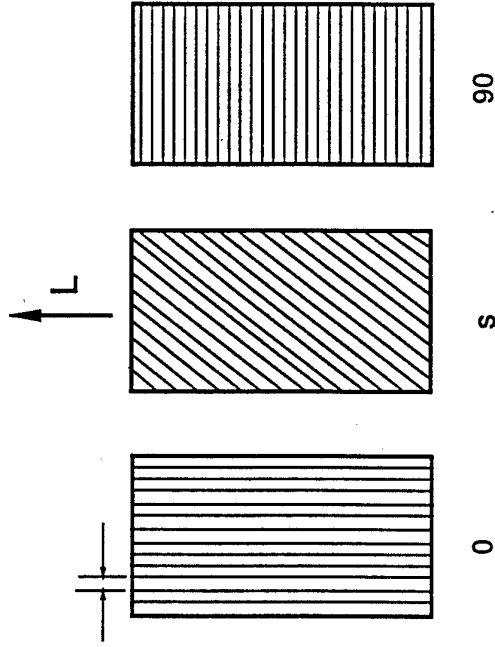
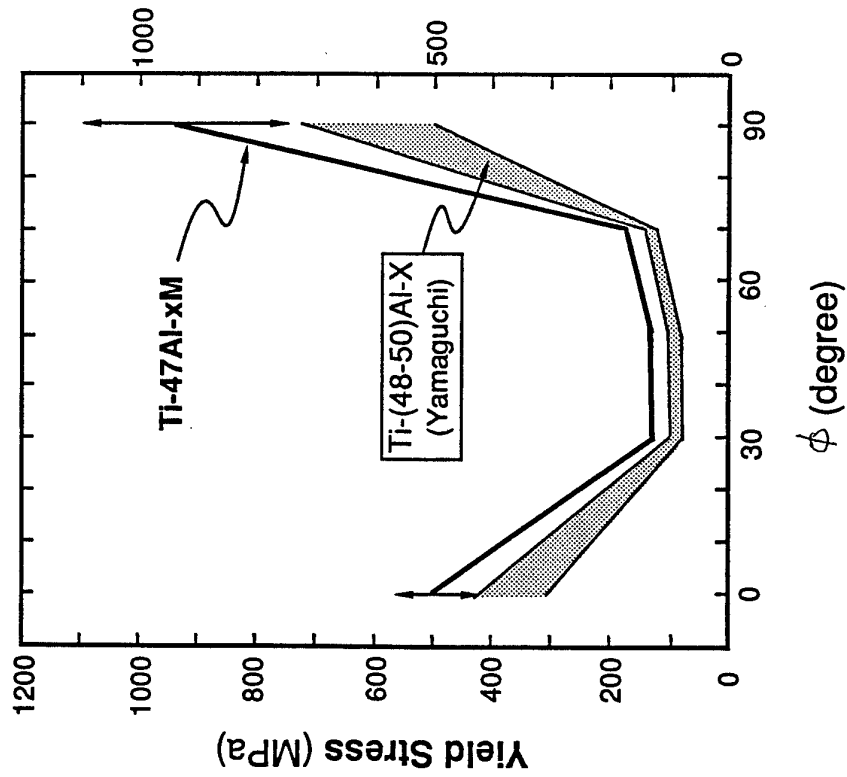
$$\sigma_y = \sigma_o + k_{d\lambda} d^{-1/2}$$

$$k_{d\lambda} = 2.5 \text{ MPa}\sqrt{\text{m}} \text{ (for } \lambda = 1 \text{ } \mu\text{m)}$$

Combined Effect of d and λ

$$k_{dy} = k_d (\tau_{\text{avg}}^* / \tau_s^*) = f_{\text{tn}} (\lambda)$$

Orientation vs. Yield-Stress in the $(\chi+\alpha_2)$ Lath Structure



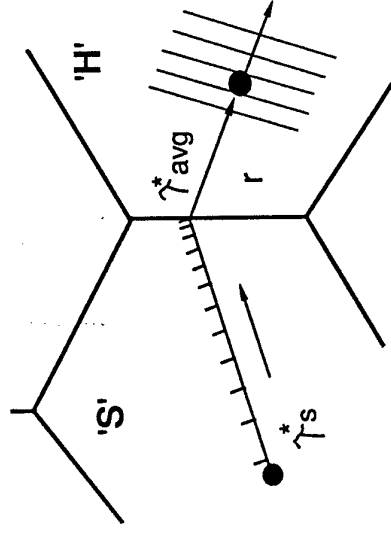
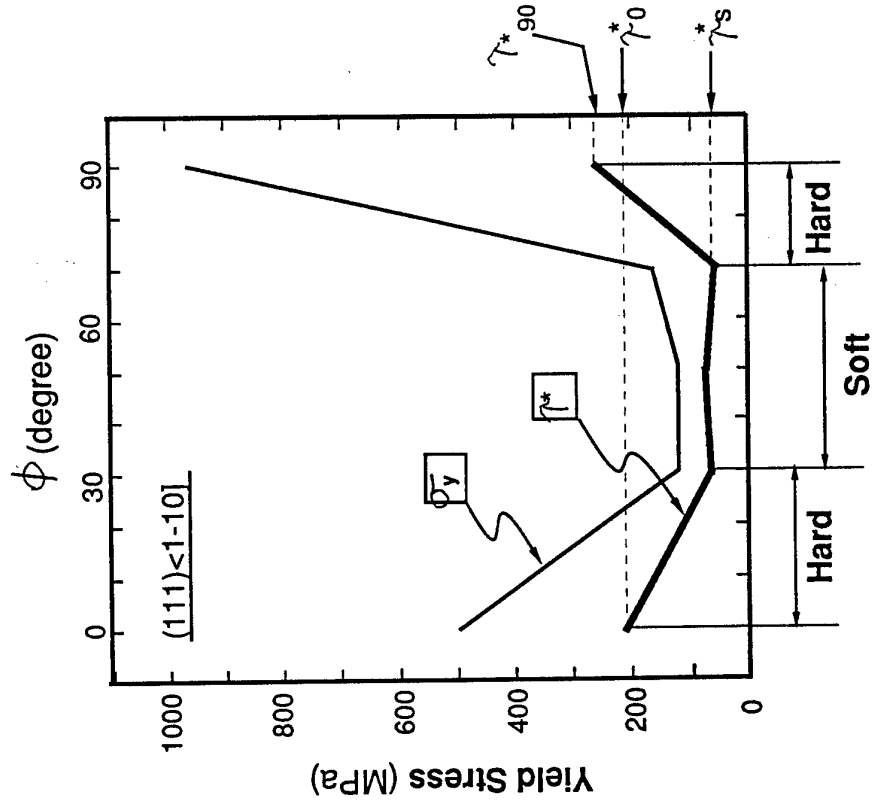
$$\bar{\sigma}_{90} : \bar{\sigma}_0 = f(\alpha_2, \chi, C)$$

$$\bar{\sigma}_{90} = \bar{\sigma}_0 + k^{-1/2}$$

$$(k = 0.5 \text{ MPa m})$$

Yielding of the (α_2) Lath Structure

Ti-(46.5-47)Al- (4-6)(Cr,V,Nb,M)

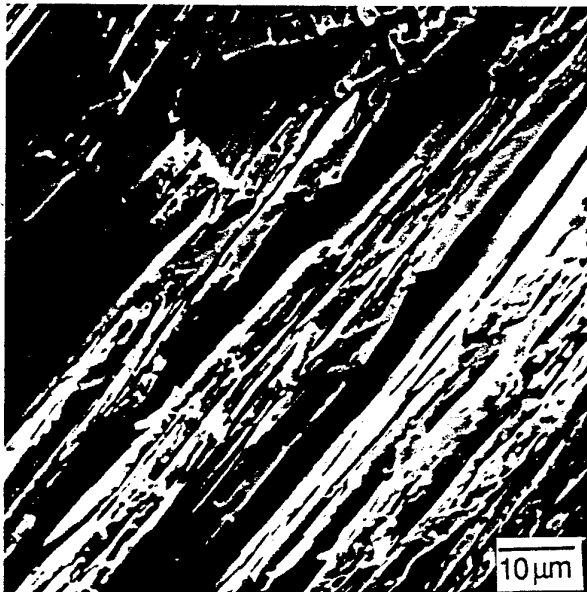
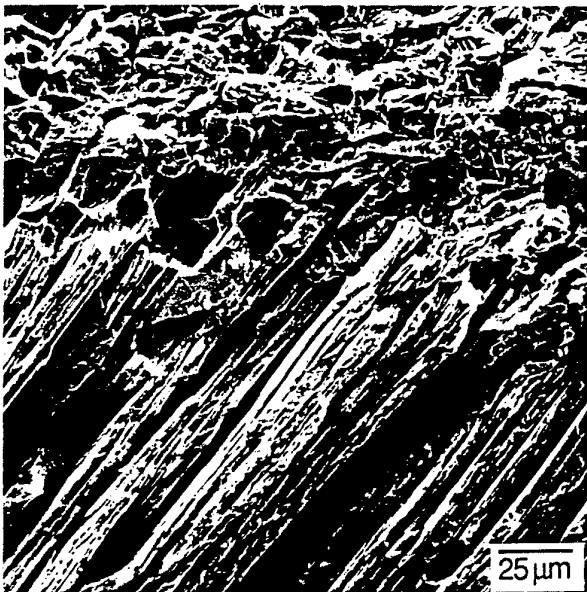
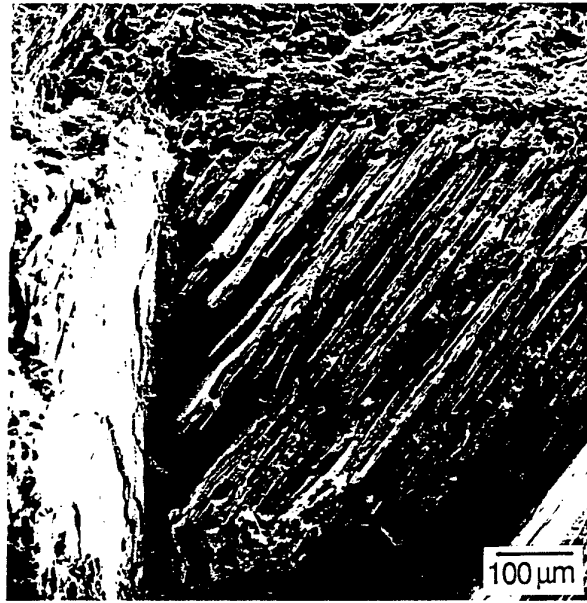
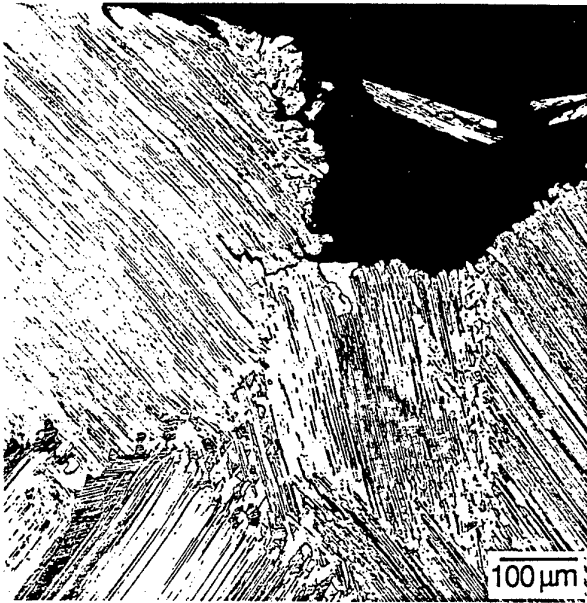


$$\tau_{avg}^* = \frac{\tau_{90}^* + \tau_0^* + 2\tau_s^*}{4} \quad (\sim 2.5 \tau_s^*)$$

τ_{avg}^* : Stress required to activate and move dislocations across lath boundaries

$$k_d = k_d (\tau_{avg}^* / \tau_s^*) \quad (\sim 2.5 k_d)$$

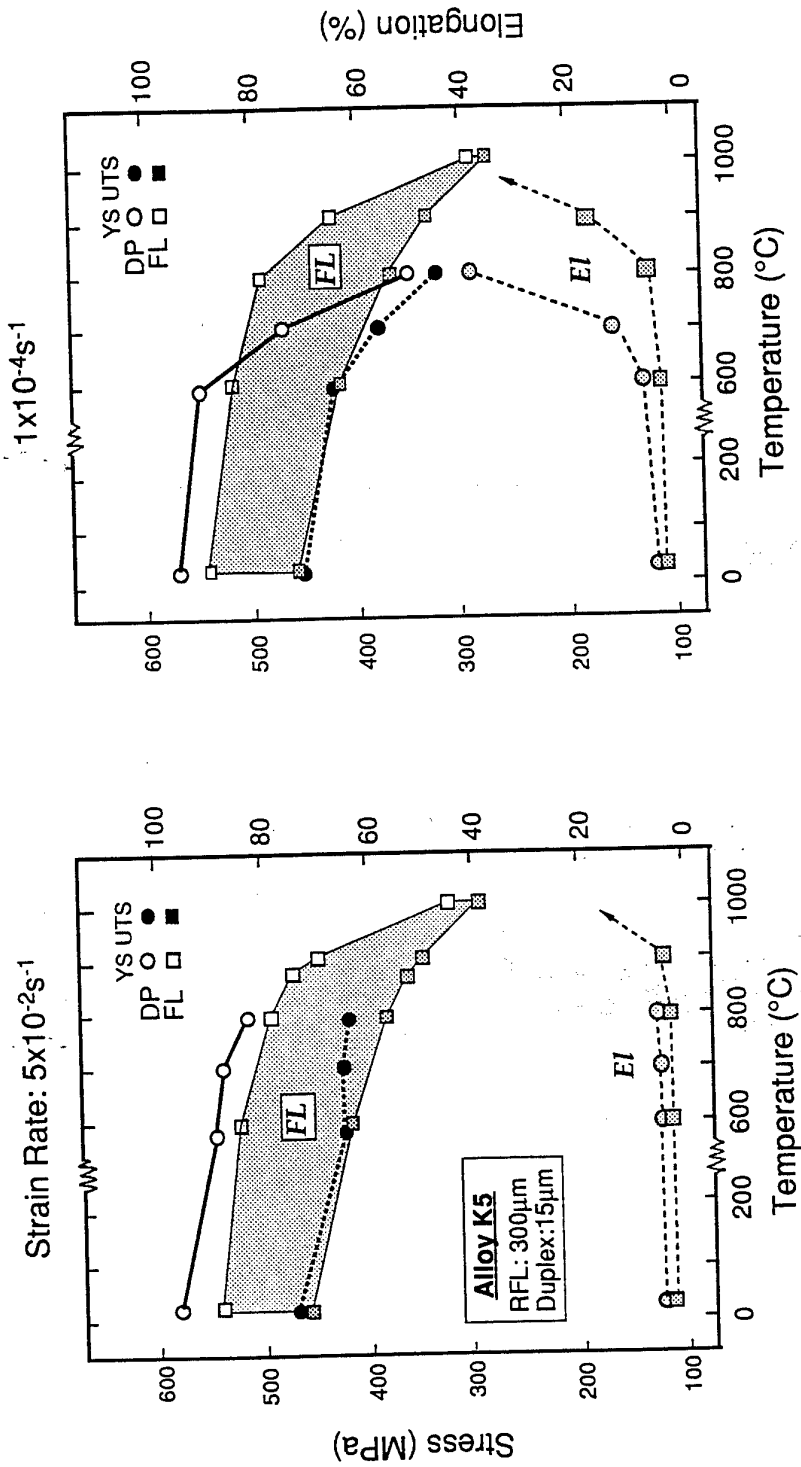
4



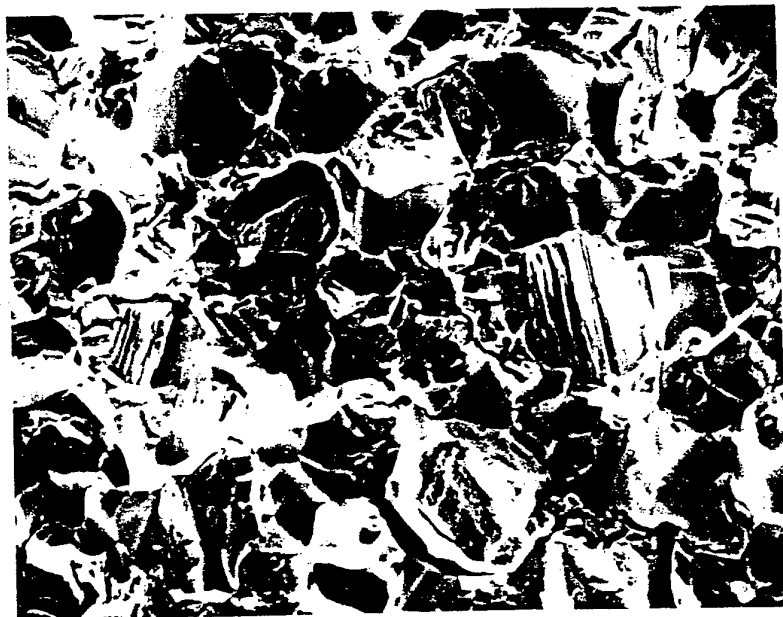
Tensile Fracture of FL Alloy G5 at 750°C

Tensile Properties of Alloy K5

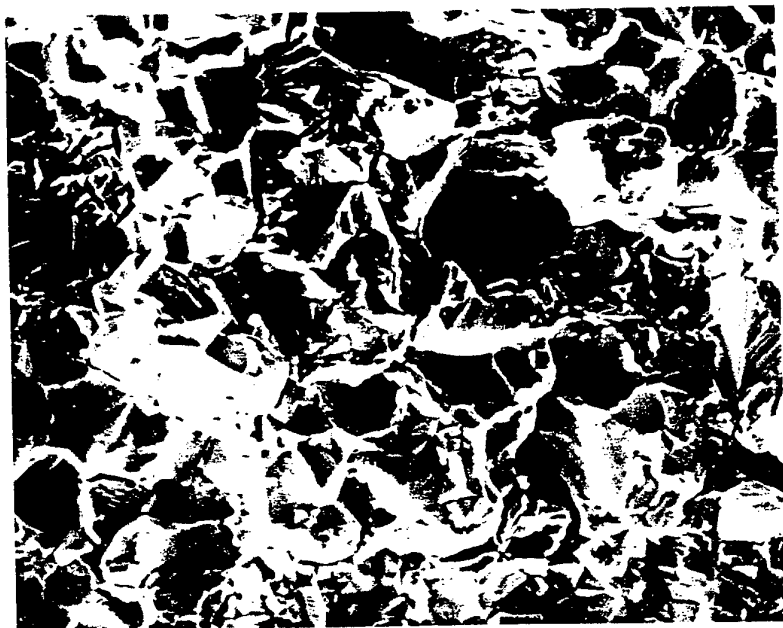
(Dependence on Microstructure, Temperature and Strain Rate)



10µm



Crack Site

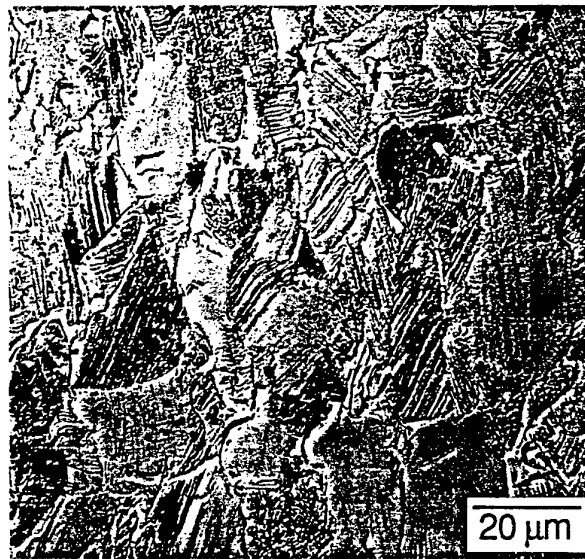


Away from Crack

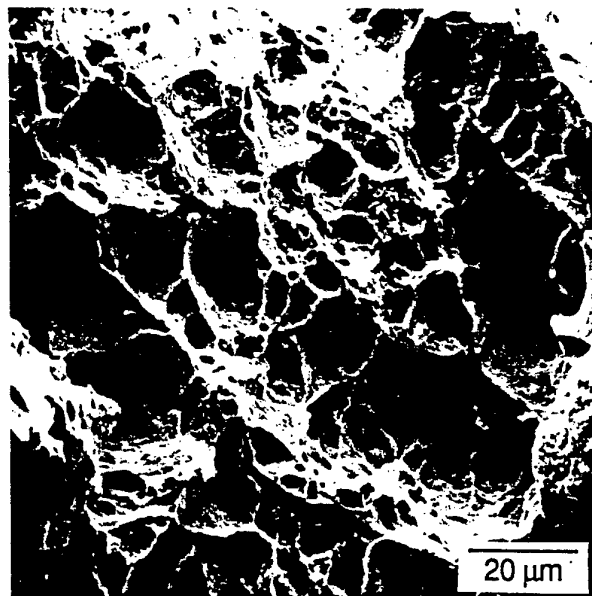
Tensile Fracture of Alloy K5 (Duplex) in Air at 600°C
[YS/UTS/EI : 396/545/3.6]



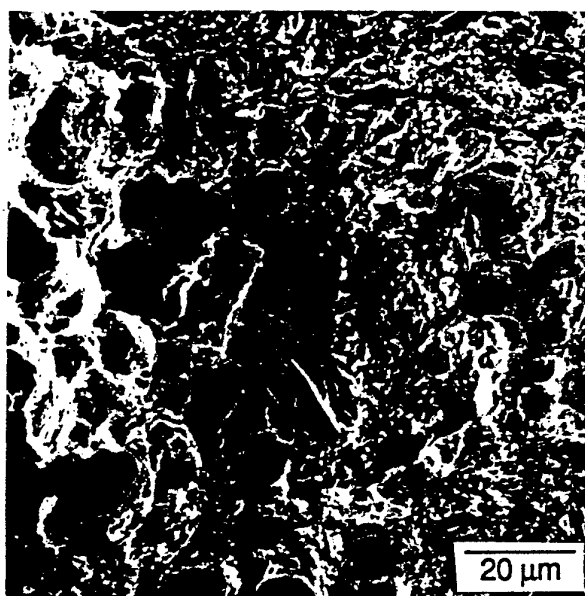
Far Below Fracture Surface



Just Below Fracture Surface



Near CI site

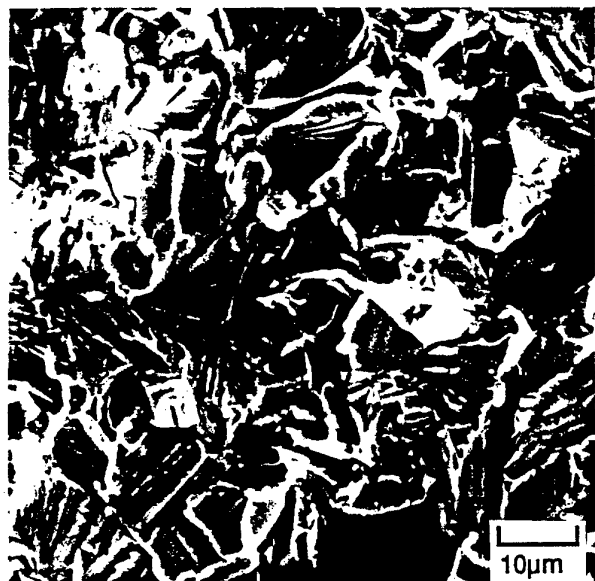


Away From CI

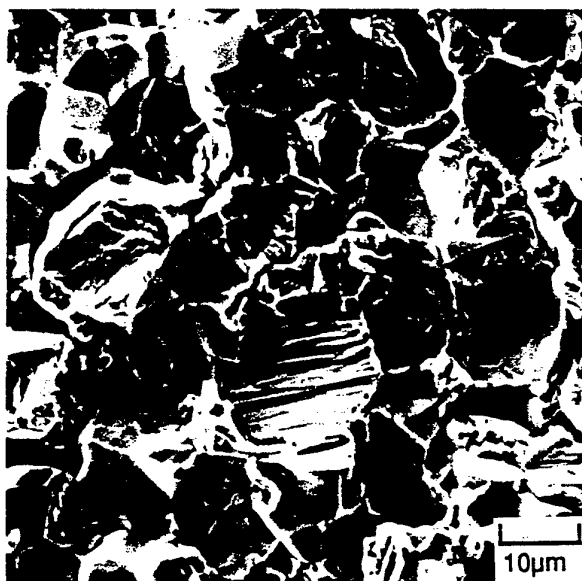
Tensile Deformation and Fracture of a Duplex Alloy K5
at 800°C in Air

Temperature Effect on Fracture Mode

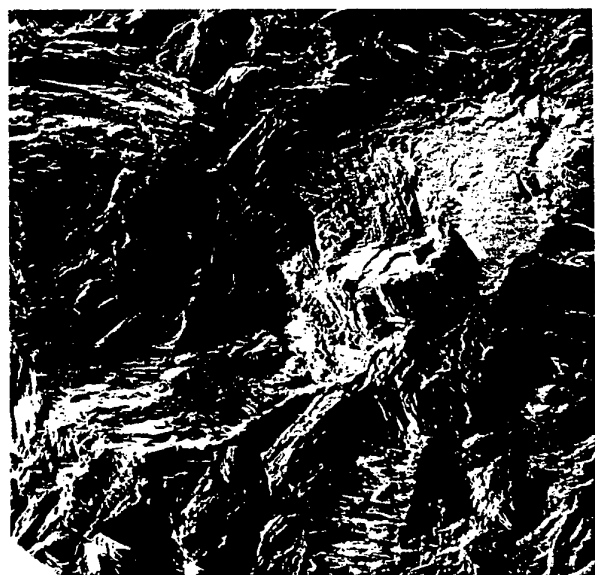
4



Duplex at RT



Duplex at 600°C



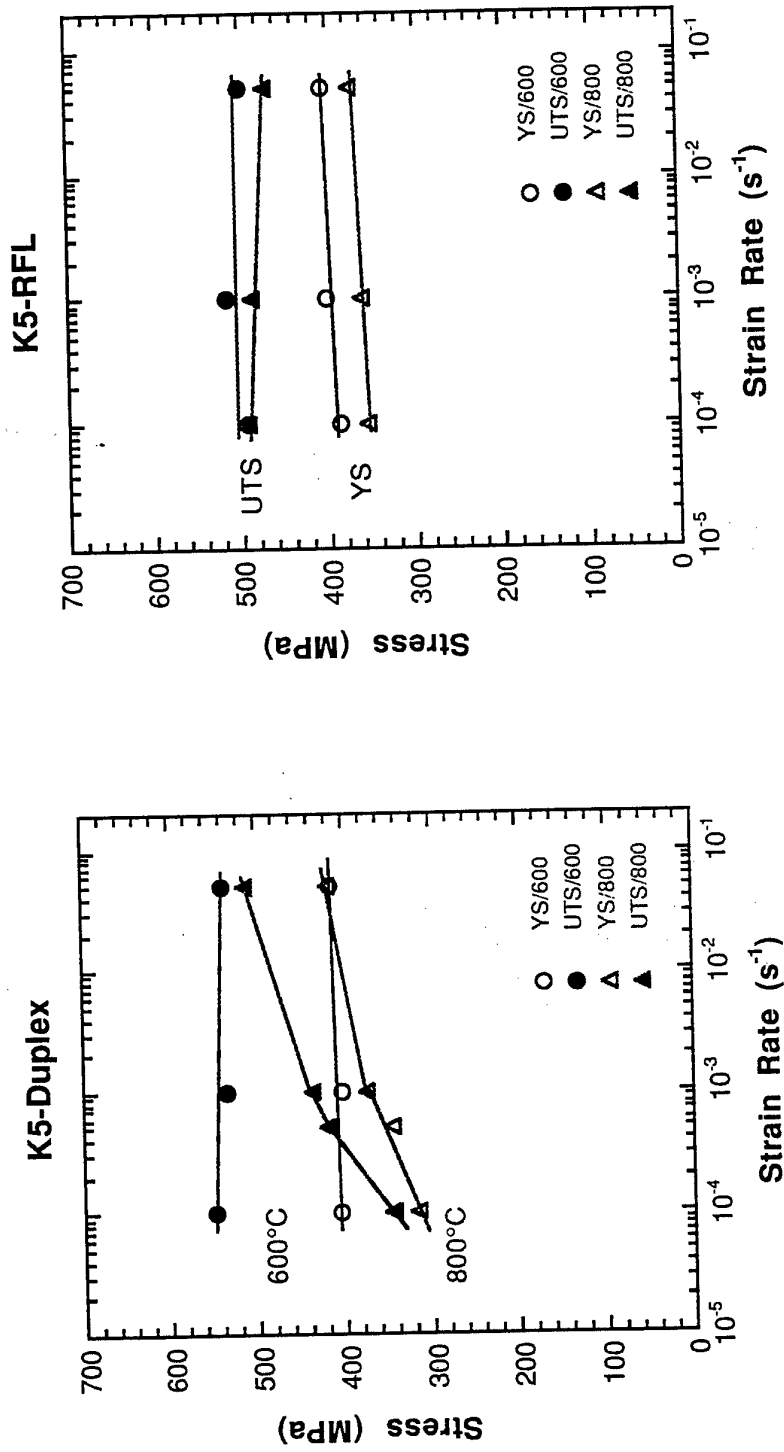
RFL at RT



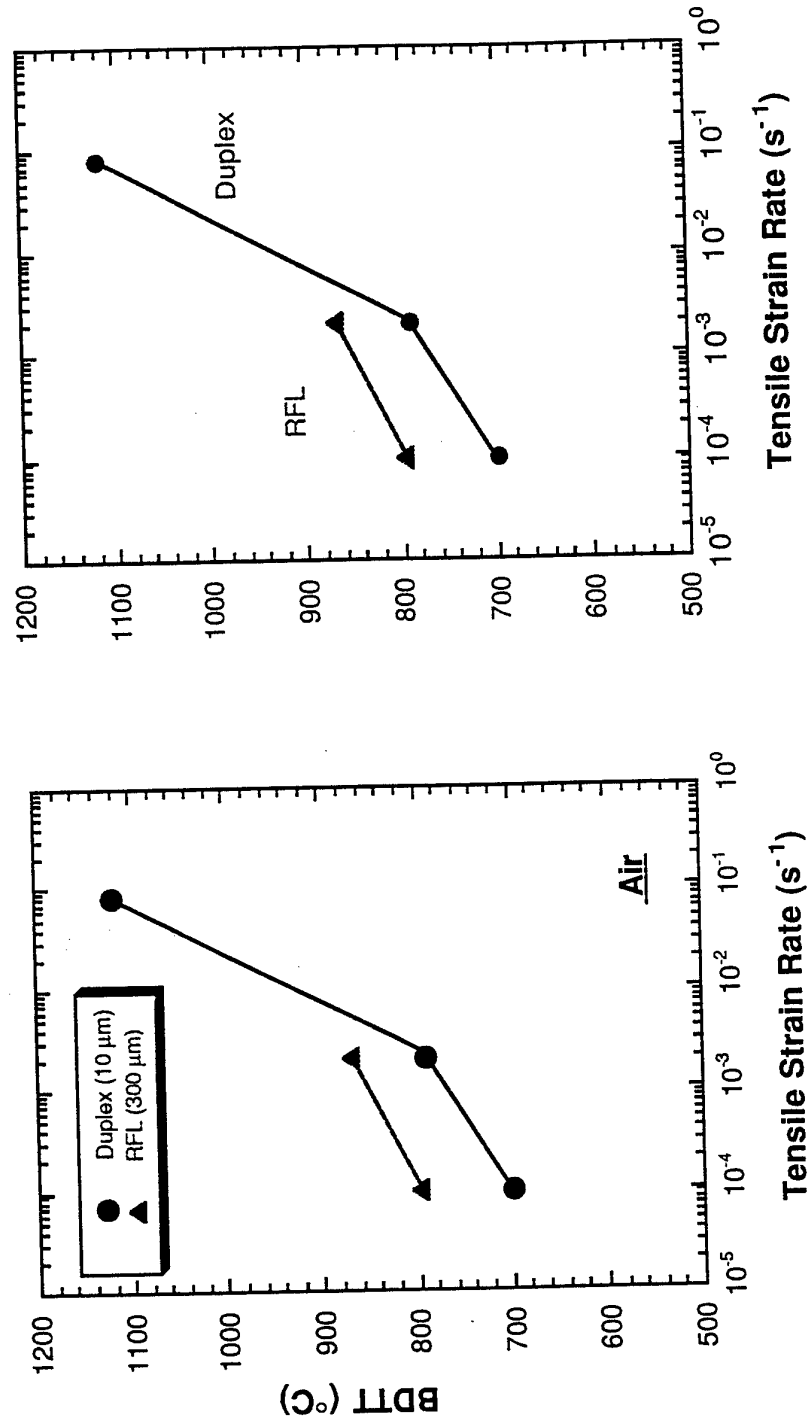
RFL at 800°C

Tensile Properties of Alloy K5

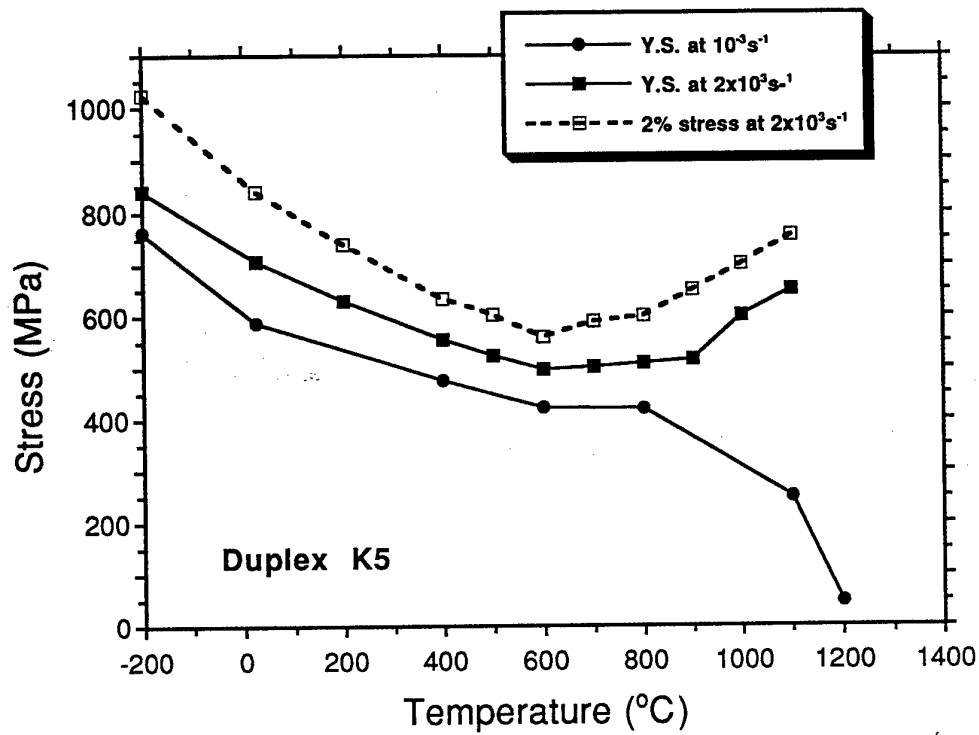
(Dependence on Microstructure, Temperature and Strain-Rate)



Effect of Strain Rate on BDT in Alloy K5



Dependence of Flow Stress on Strain-Rate and Temperature



Jin + Kim (95)

Factors Controlling Tensile Properties

Microstructure

Types: Duplex vs. FL

Features

Grain Size and Morphology

GB Morphology

Lamellar Spacing (LS)

α_2/γ Ratio (α_2 vol%)

Uniformity

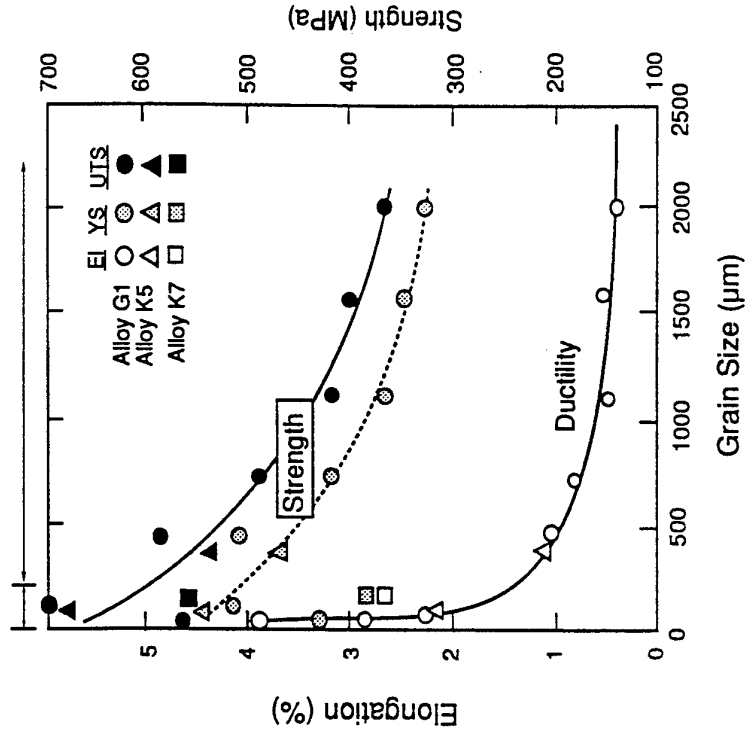
Composition

α_2/γ Ratio; LS

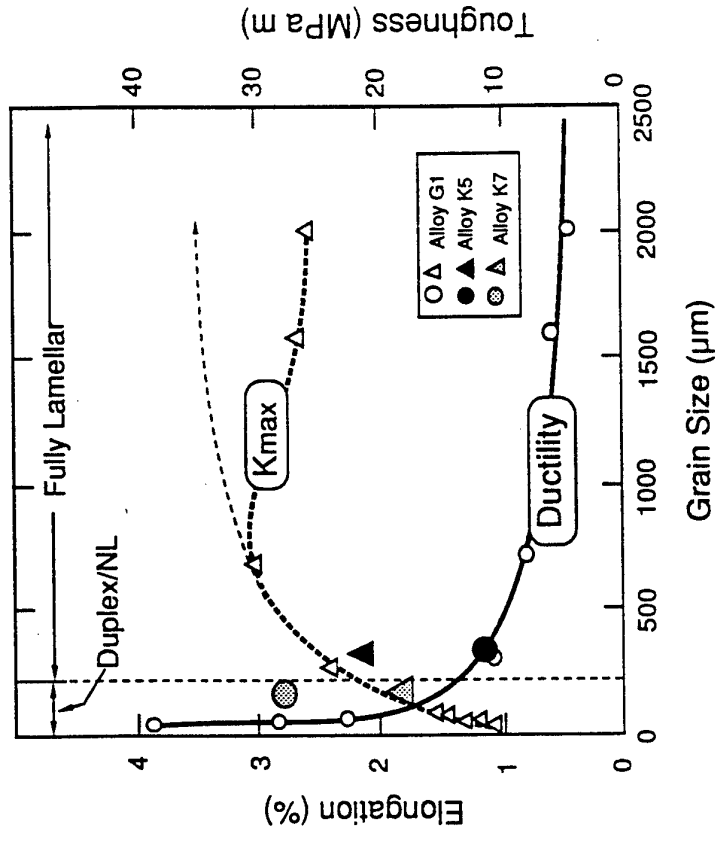
Cleavage Strength

Interfacial Bond Strength

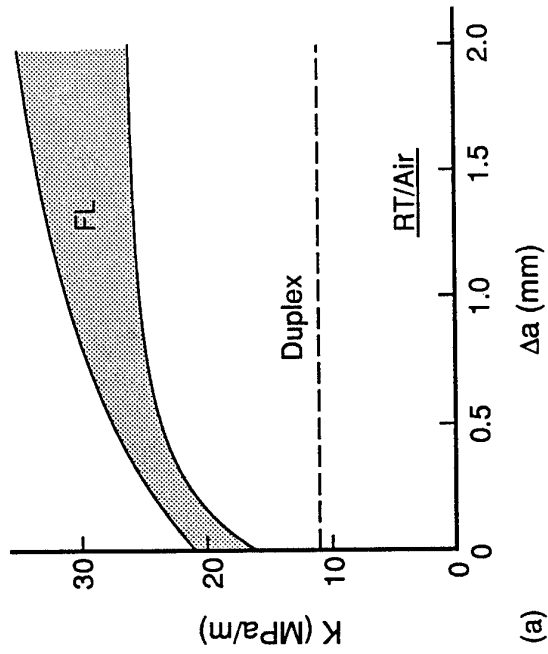
Grain Size Effects on Tensile and Toughness



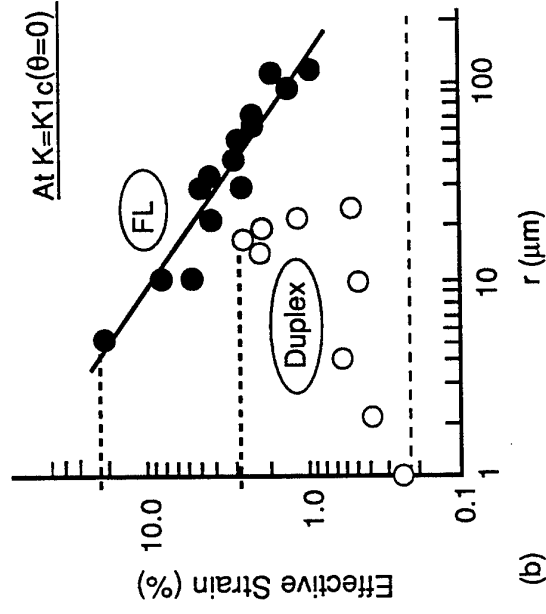
Ductility and Strength



Ductility and Toughness

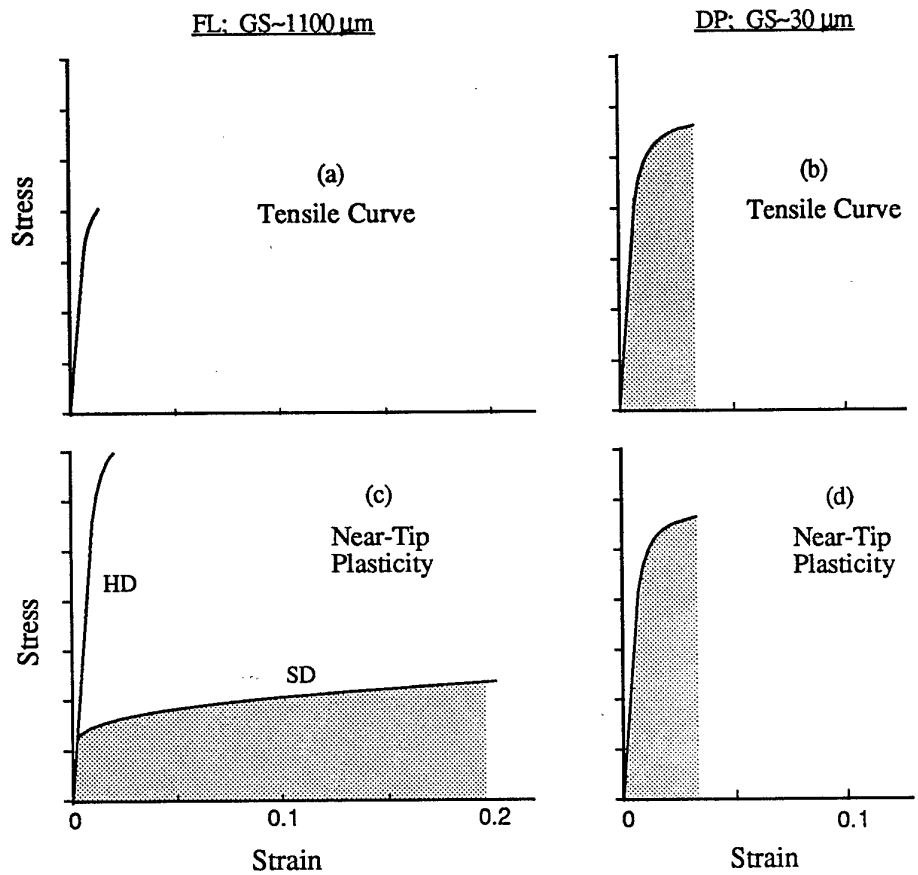


K-Resistance Curves

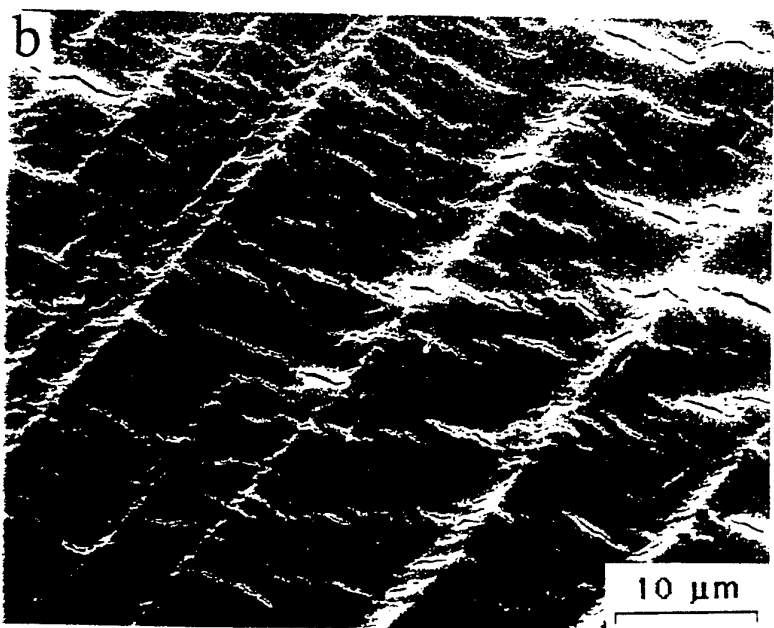
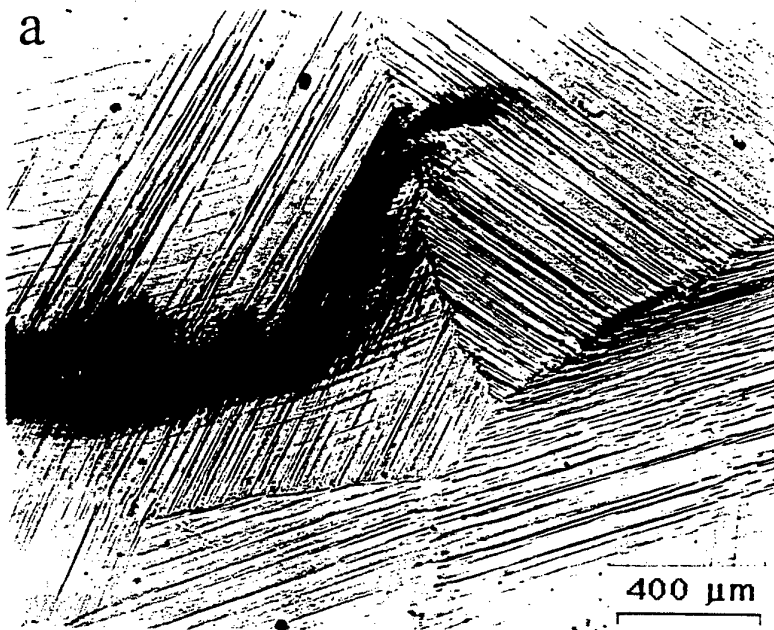


Near-tip Strain Distribution

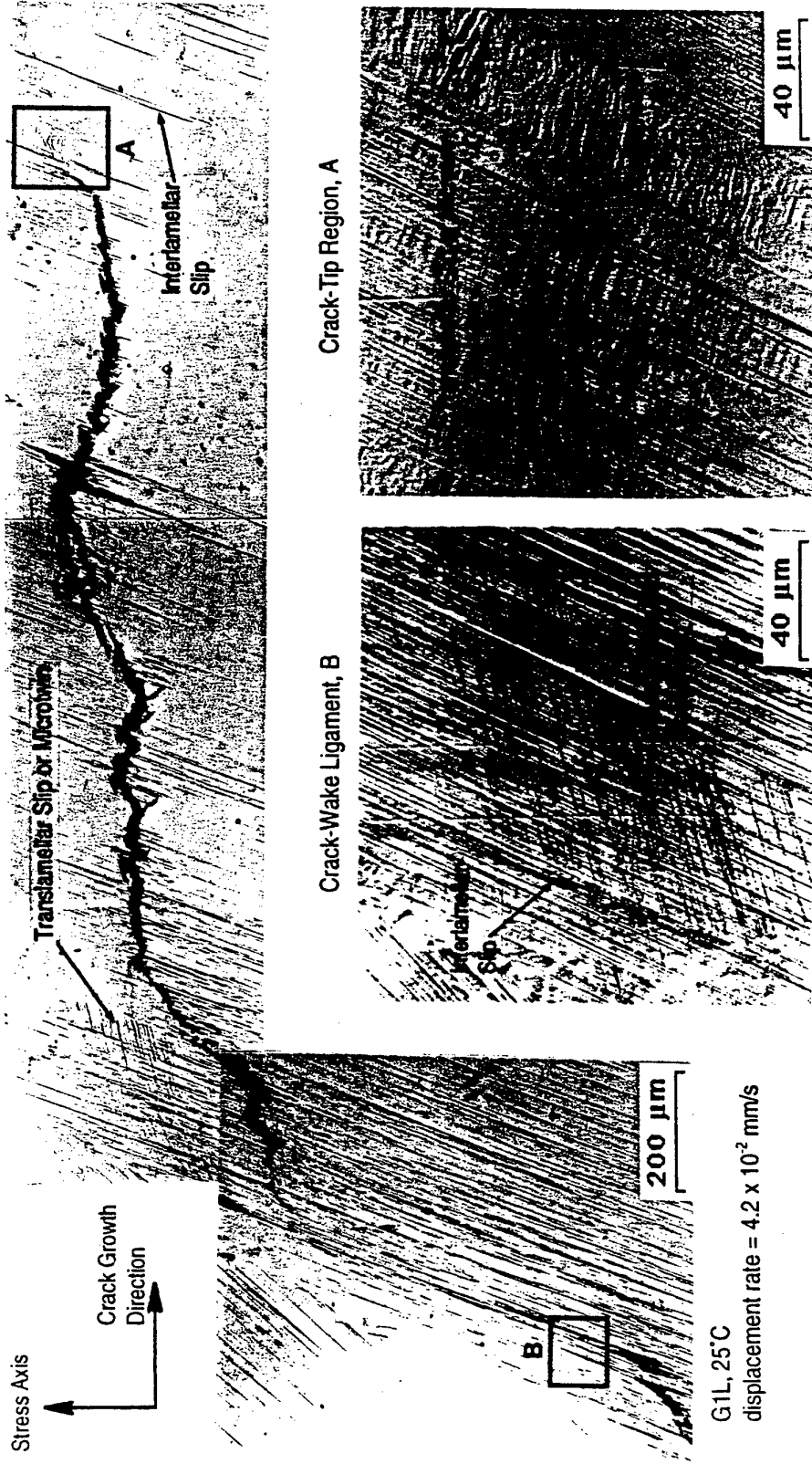
Fracture Resistance and Near-Tip Plasticity at RT



General Tensile Yielding vs. Near-Crack-Tip Plasticity at K_{Ic}



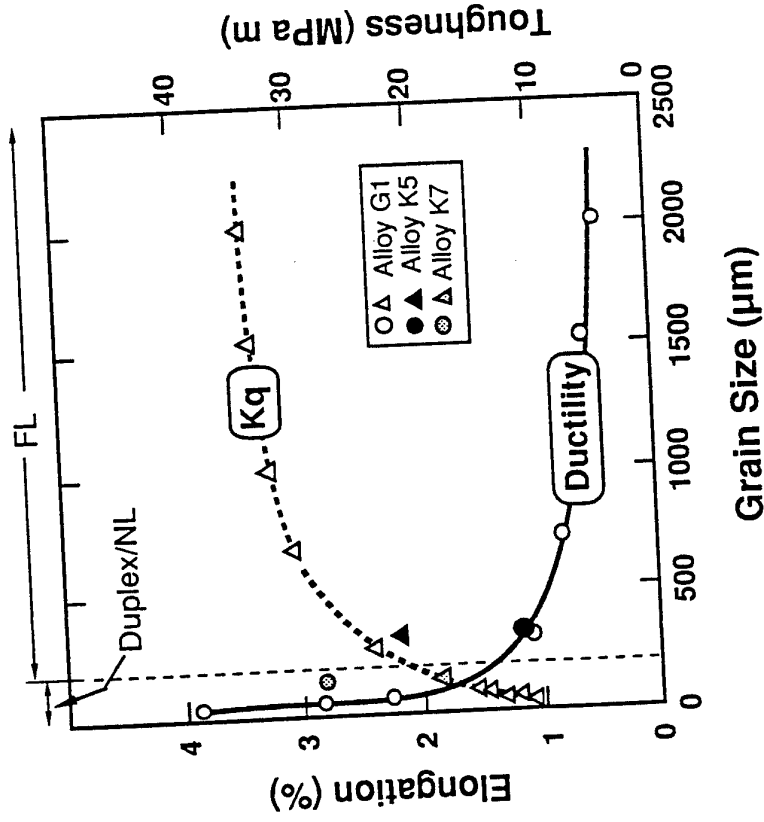
Plastic Deformation and Microvoiding Around the Advancing Crack Tip in a FL Alloy G1 CT Specimen under a Monotonic Tension Loading at RT



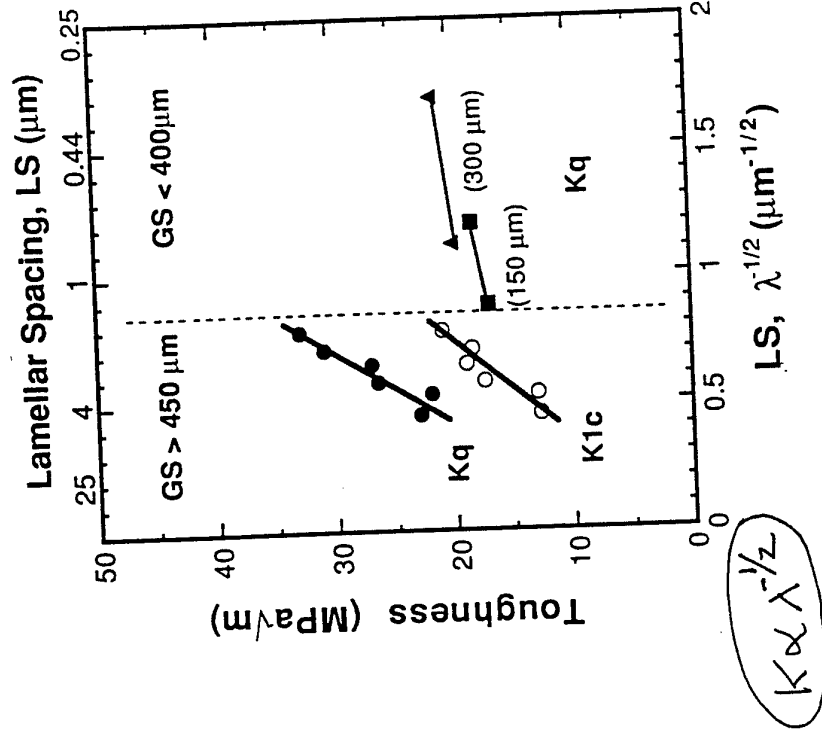
Interlamellar and Translamellar Deformation in Crack-Tip and Ligament Regions

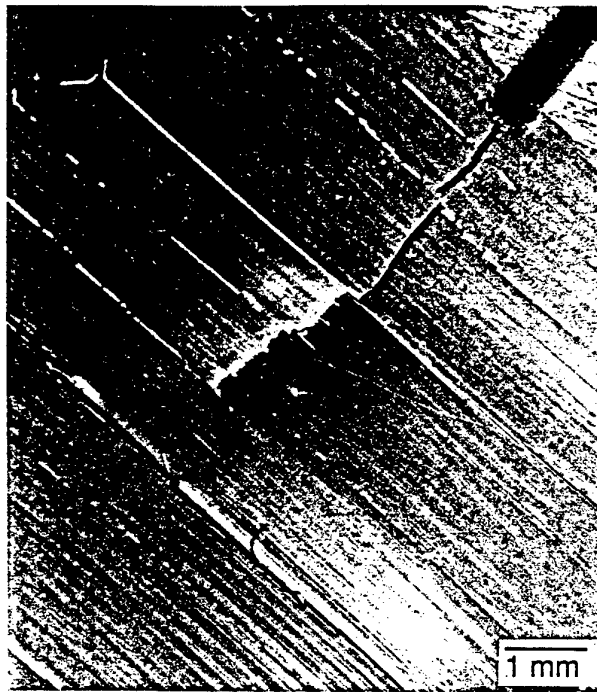
Fracture Toughness

Grain Size Effect

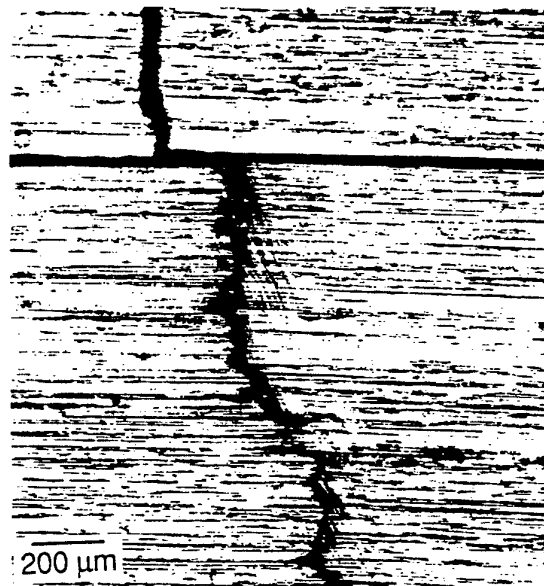


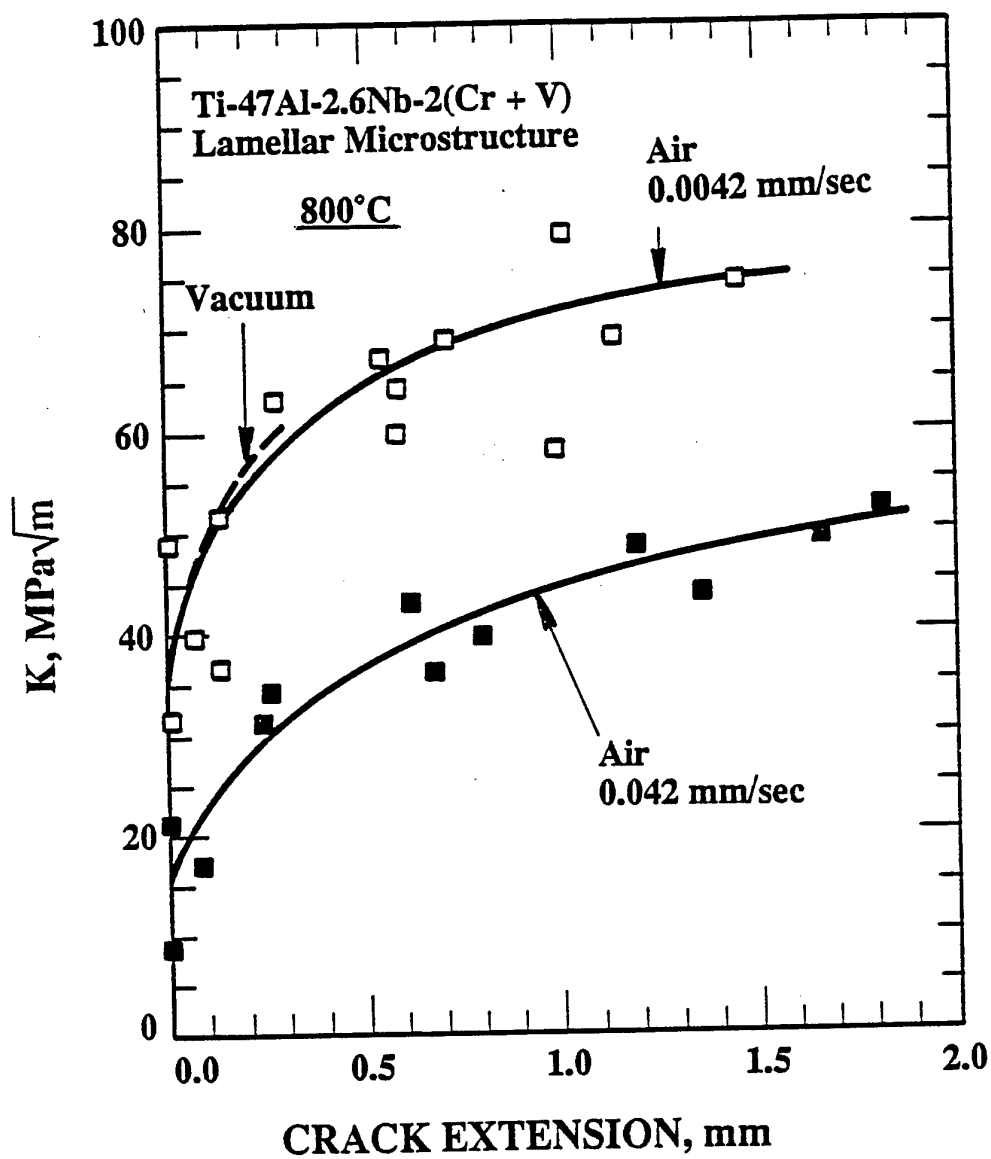
Lamellar Spacing Effect





T-Cracks Involving
Delamination, and Both
Inter- and Trans-lamellar
Slip/Twinning





Effect of displacement rate on the K-resistance curves of the G1L alloy at 800°C.



48

41

39

36 MPa√m

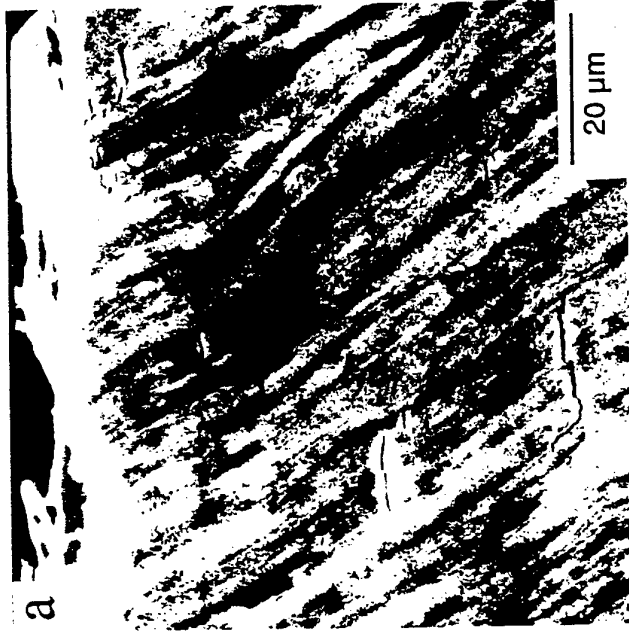


57

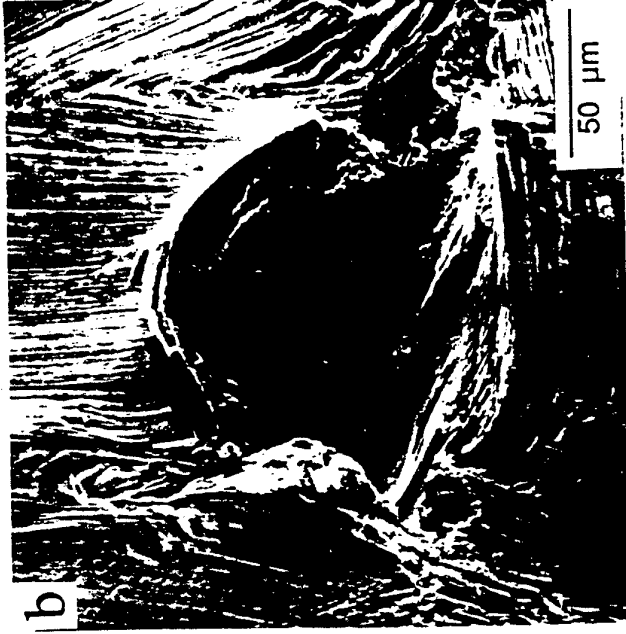
52

50

Fracture Process in Lamellar TiAl Alloys at 800°C



RT

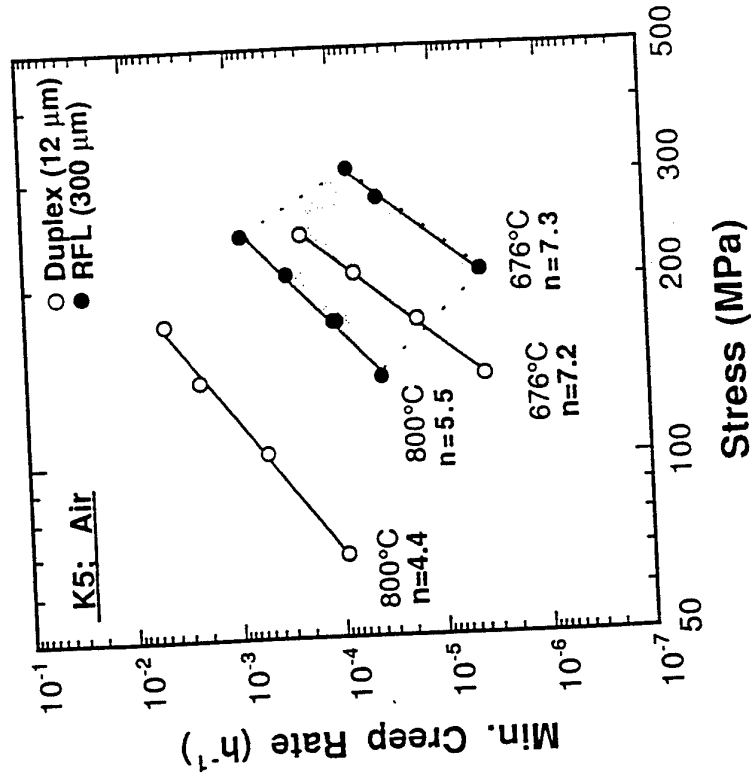


800°C

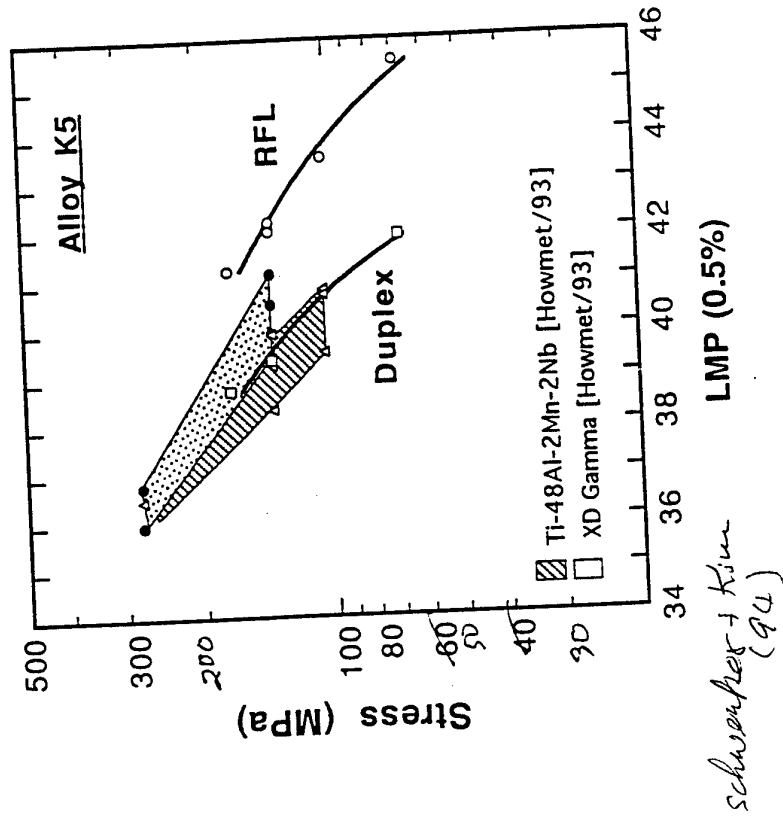
Crack-Tip Regions of Lamellar TiAl Fracture Specimens

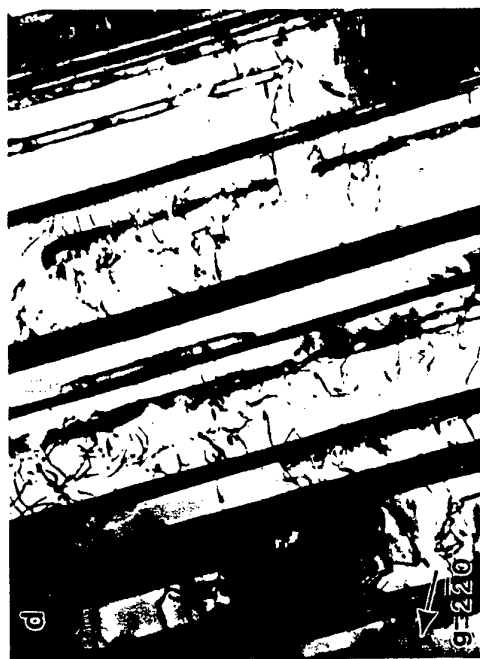
Creep Resistance of Alloy K5

Stress Exponents



Larsen-Miller Plot

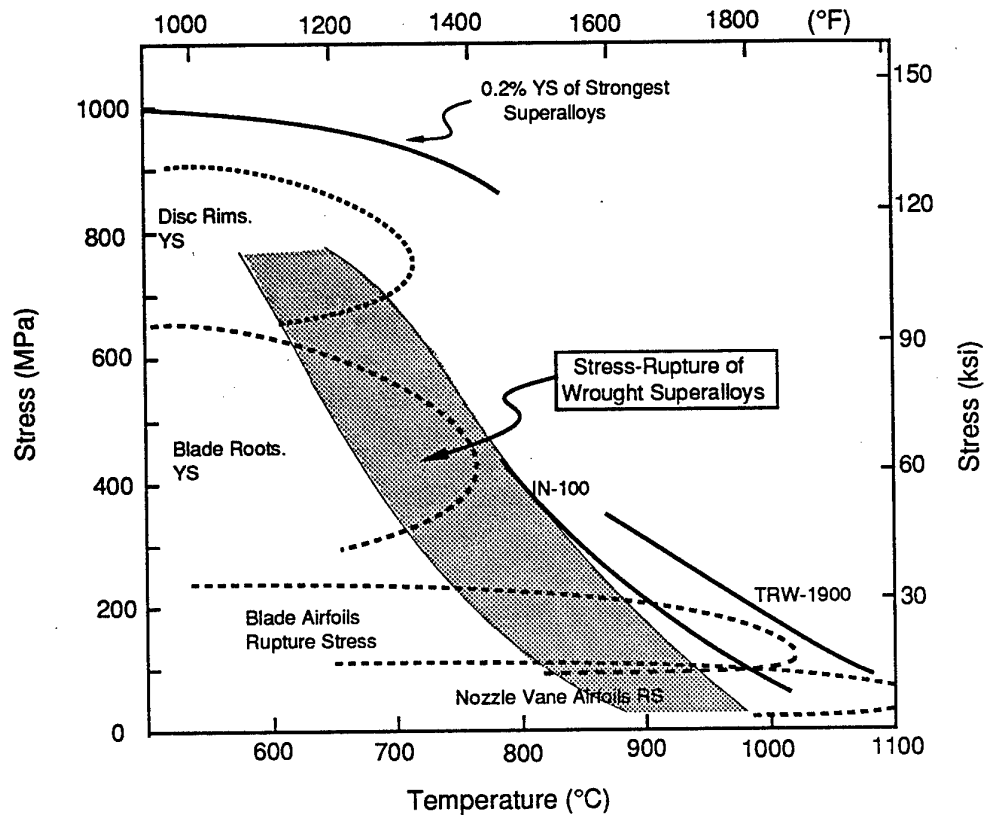




Alloy G1 : Lamellar structure near the fracture surface of the specimen crept in vacuum at 207 MPa



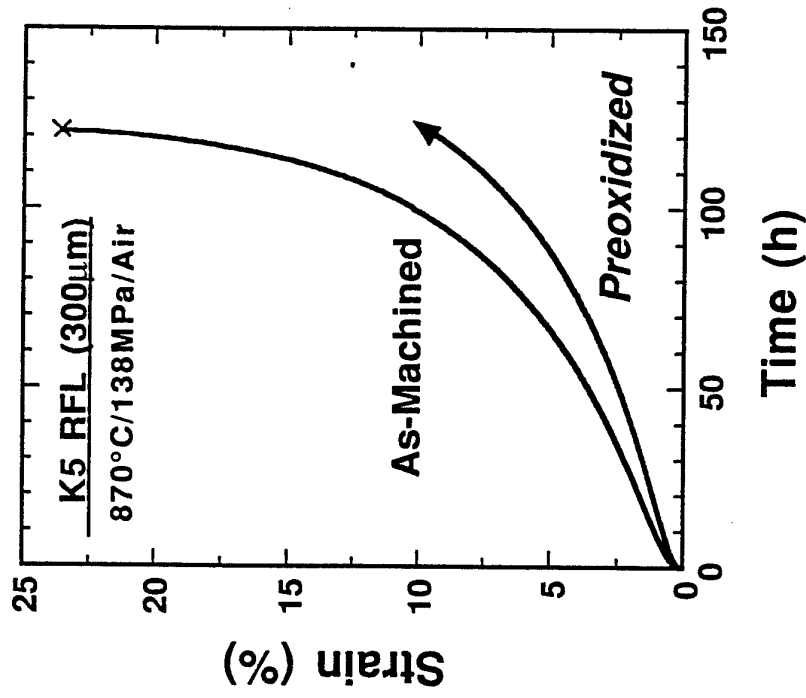
Alloy K5 RFL Specimen Crept at 800°C to 18.7% in Air Under
(138-173-207-242-285 MPa) Step Stress Conditions



Turbine Blade and Vane Operating Temperatures, Yield Stresses (YS), 1000-h Rupture Stresses (RS) for Superalloys

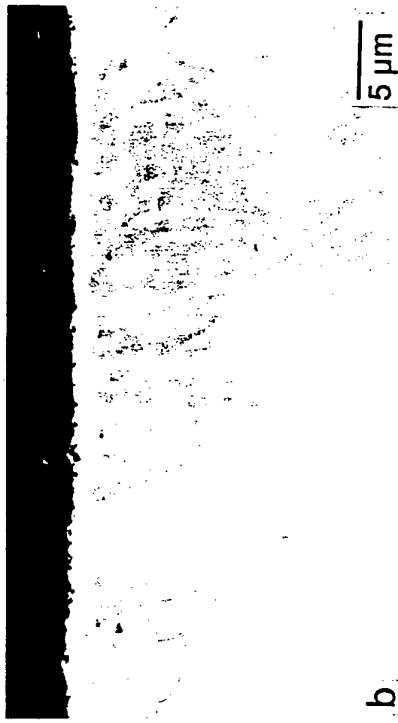
Effect of Al_2O_3 Layer on Creep

Creep of Alloy K5



a

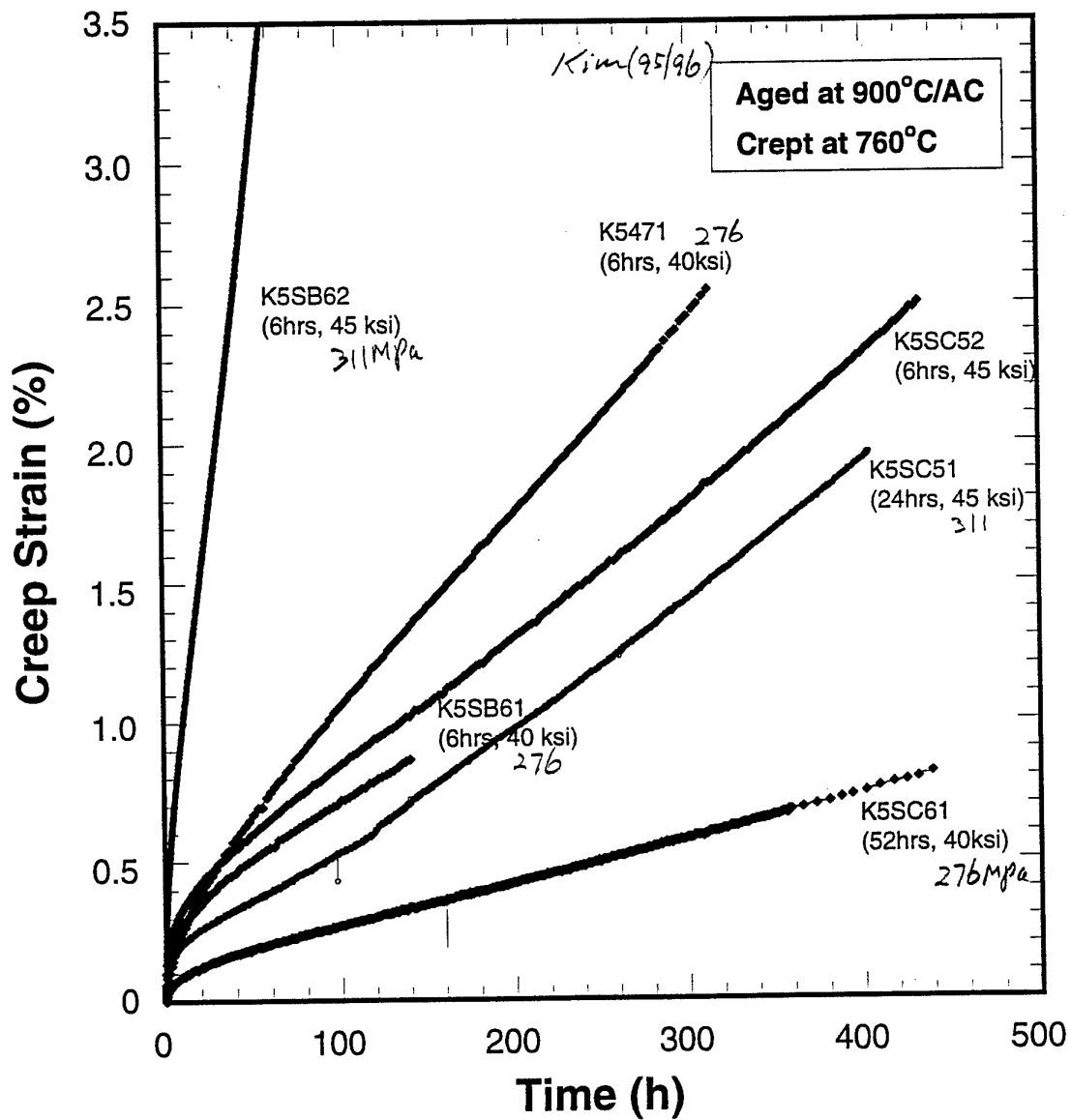
5 μm



b

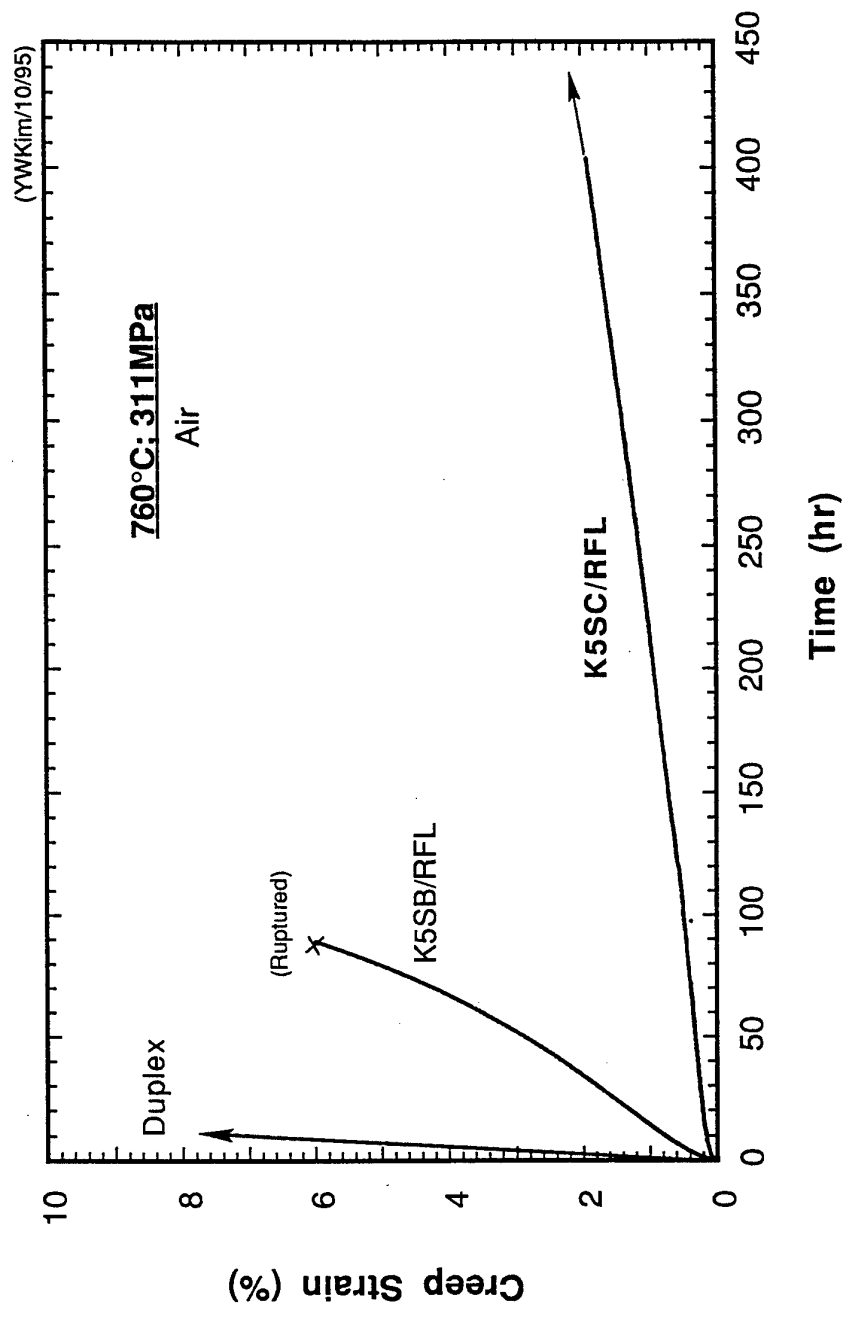
5 μm

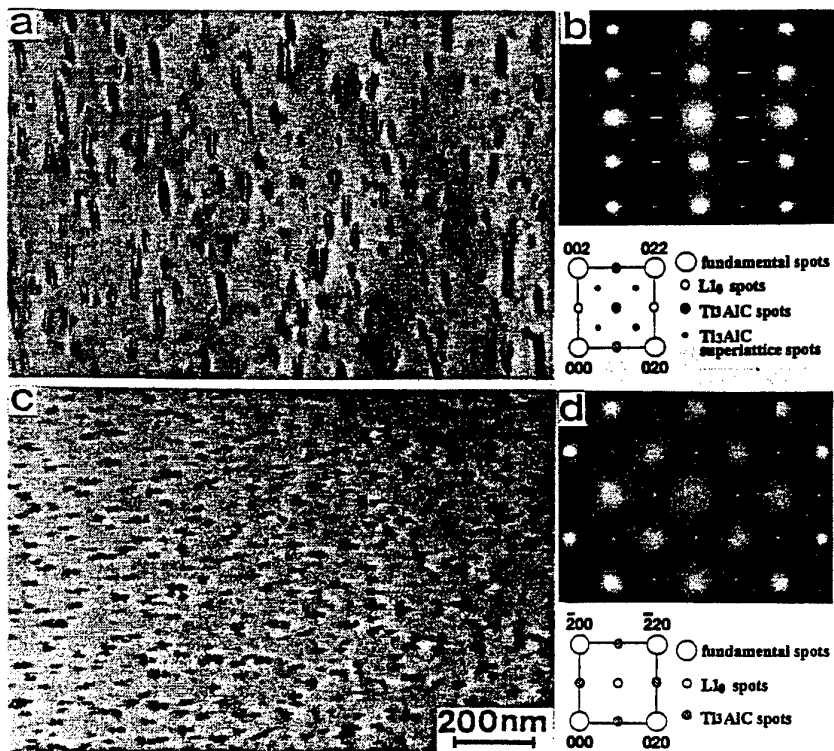
Al_2O_3



Creep of Alloy K5 Series

(under severe conditions)





Nemoto (94)

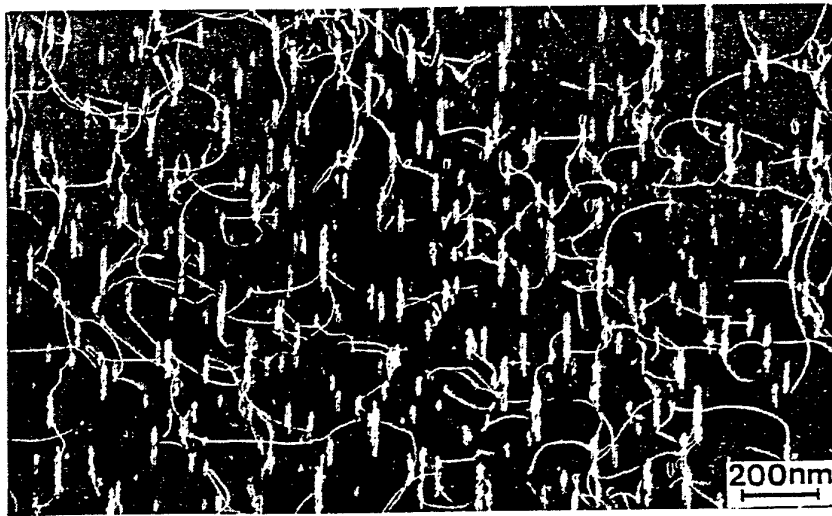


Figure 8 Dark field electron micrograph showing the bypassing dislocations in $(\text{Ti}_{0.49}\text{Al}_{0.51})_{99.5}\text{C}_{0.5}$ aged at 1073 K for 3.6×10^5 s (100h/over aged) and deformed to 3% at 873 K. The dislocation loops surrounding needles can be seen.

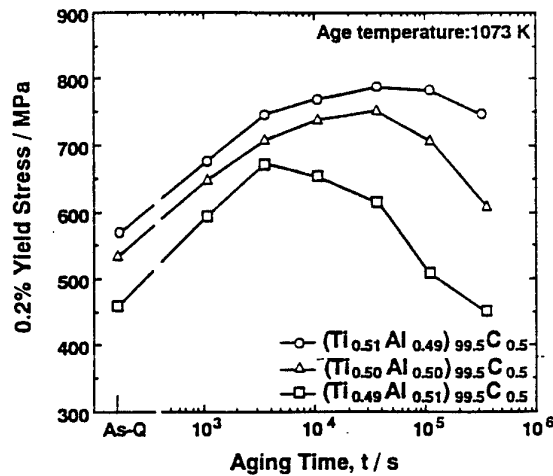


Figure 2 Effects of the deviation from the stoichiometry on the variation of compressive yield strength of $(\text{Ti}_{0.51}\text{Al}_{0.49})_{99.5}\text{C}_{0.5}$, $(\text{Ti}_{0.50}\text{Al}_{0.50})_{99.5}\text{C}_{0.5}$ and $(\text{Ti}_{0.49}\text{Al}_{0.51})_{99.5}\text{C}_{0.5}$ during aging at 1073 K.

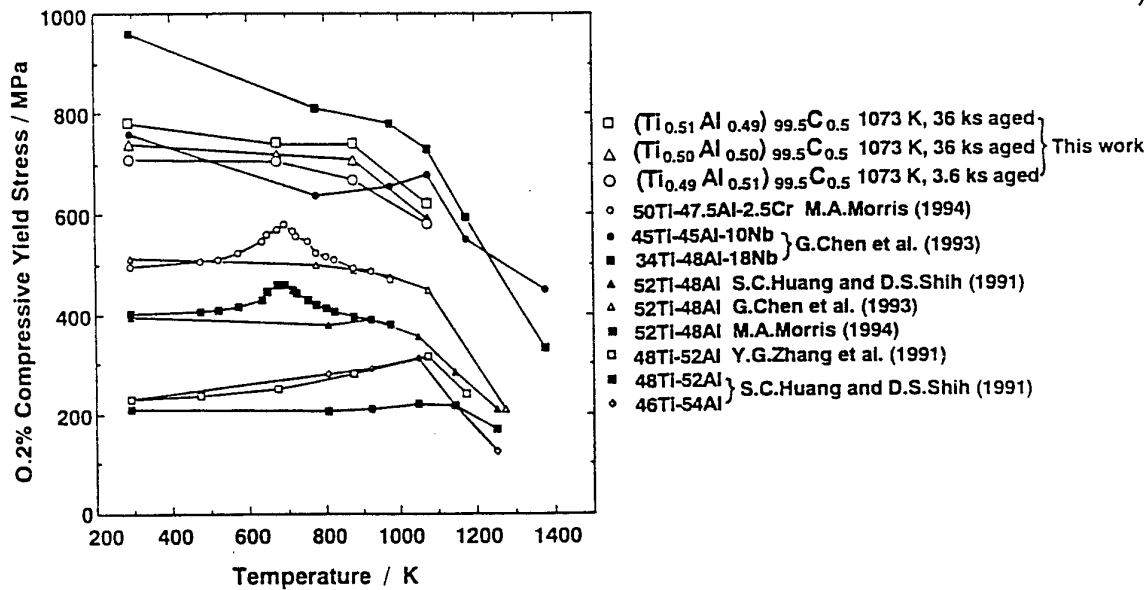
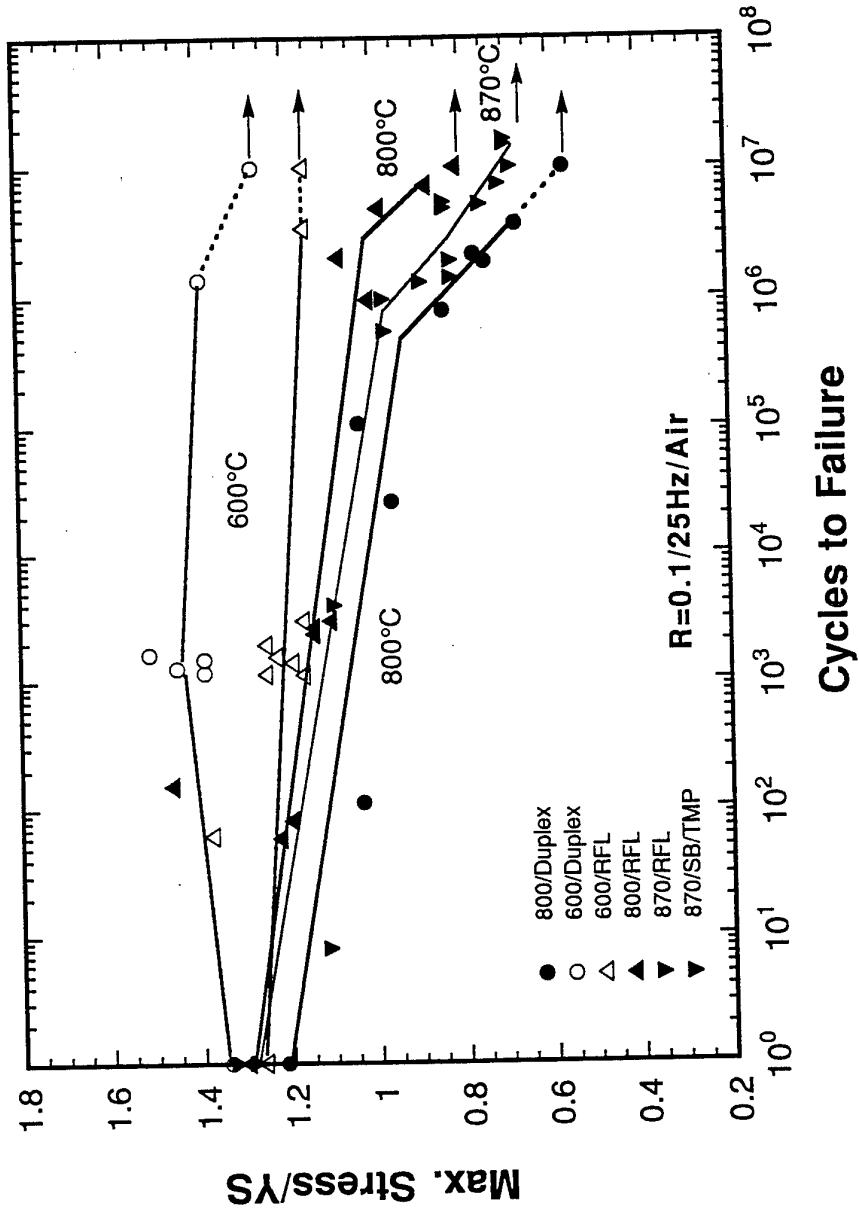


Figure 3 Temperature dependence of compressive yield strength of $(\text{Ti}_{0.51}\text{Al}_{0.49})_{99.5}\text{C}_{0.5}$ and $(\text{Ti}_{0.50}\text{Al}_{0.50})_{99.5}\text{C}_{0.5}$ aged at 1073 K for 3.6×10^4 s (10 h), and $(\text{Ti}_{0.49}\text{Al}_{0.51})_{99.5}\text{C}_{0.5}$ aged at 1073 K for 3.6×10^3 s (1 h). Data for binary and ternary TiAl are also included.

HCF of Alloy K5



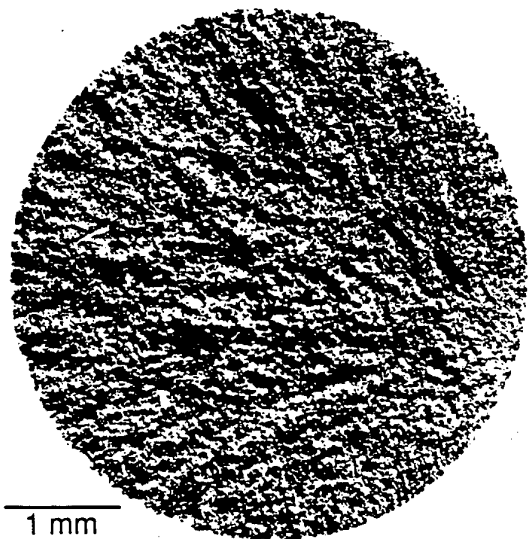


$\sigma_m = 430 \text{ MPa}$; $C_f = 2,310$

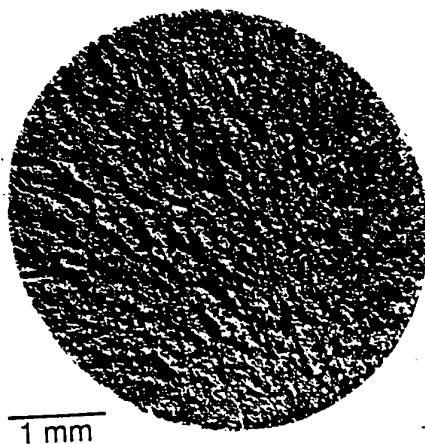
$\sigma_m = 330 \text{ MPa}$; $C_f = 7.2 \times 10^6$

Fatigue Deformation and Fracture of FL Alloy K5 at
800°C and $R=0.1$ in Air (UTS = 500 MPa)

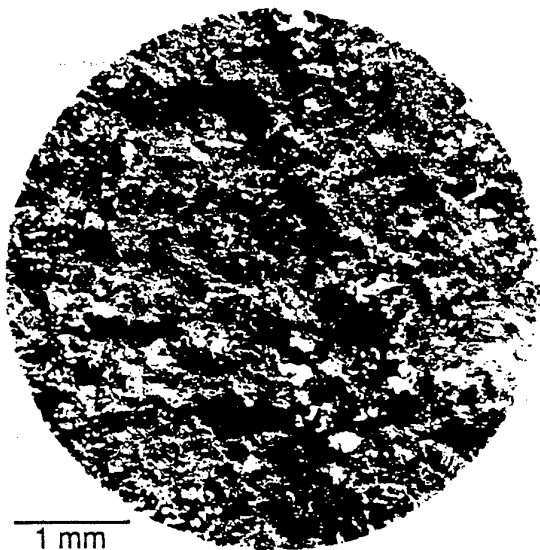
4



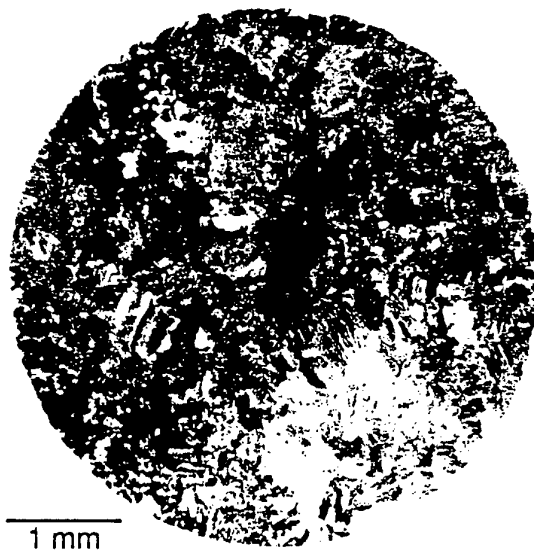
$\sigma_m/UTS=430/505$ MPa ; $C_f=10,700$



$\sigma_m/UTS=280/505$ MPa ; $C_f=3.6 \times 10^6$



$\sigma_m/UTS=430/500$ MPa ; $C_f=2,310$



$\sigma_m/UTS=330/500$ MPa ; $C_f=7.2 \times 10^6$

Fatigue Fracture of Alloy K5 in Various Conditions
at 800°C and $R = 0.1$ in Air

Load-Controlled Fatigue Failure of FL Alloy K5

(R=0.1 / 870°C / Air)



$\sigma_{\max}=350 \text{ MPa} / N_f=9.6 \times 10^5$



$\sigma_{\max}=250 \text{ MPa} / N_f=1.63 \times 10^7$



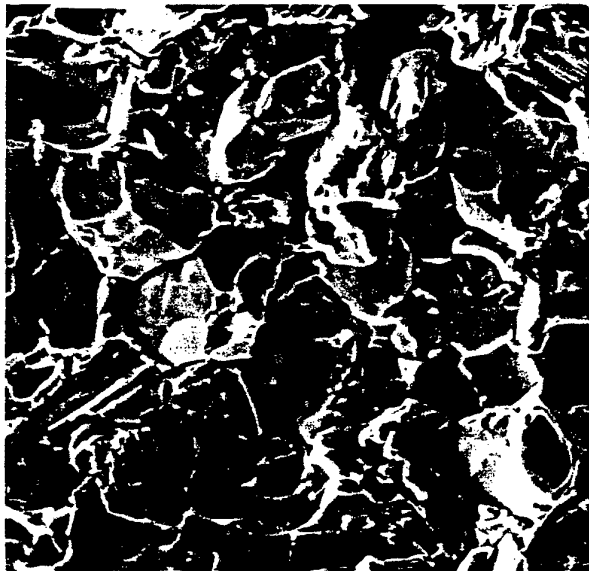


Near Cl Site

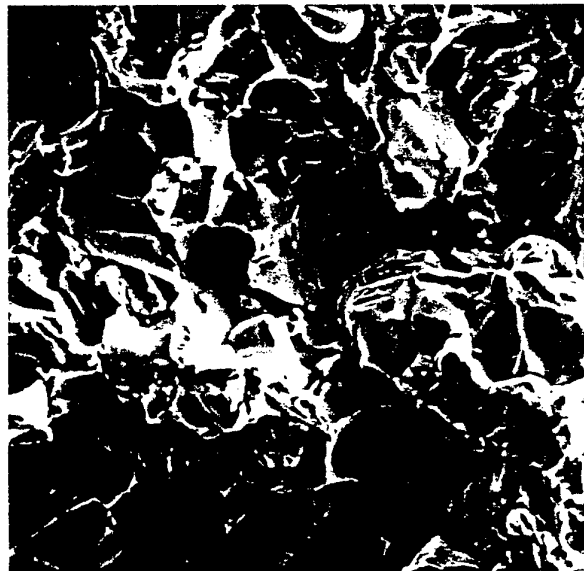


Near Cl

10 μm



Away from Cl



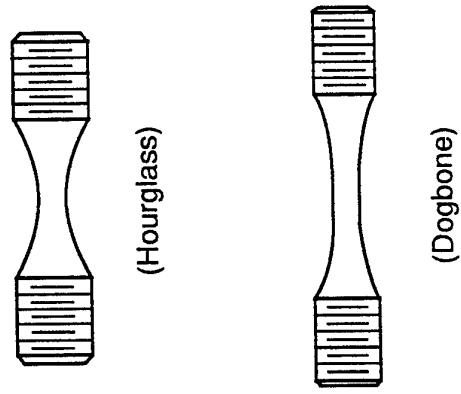
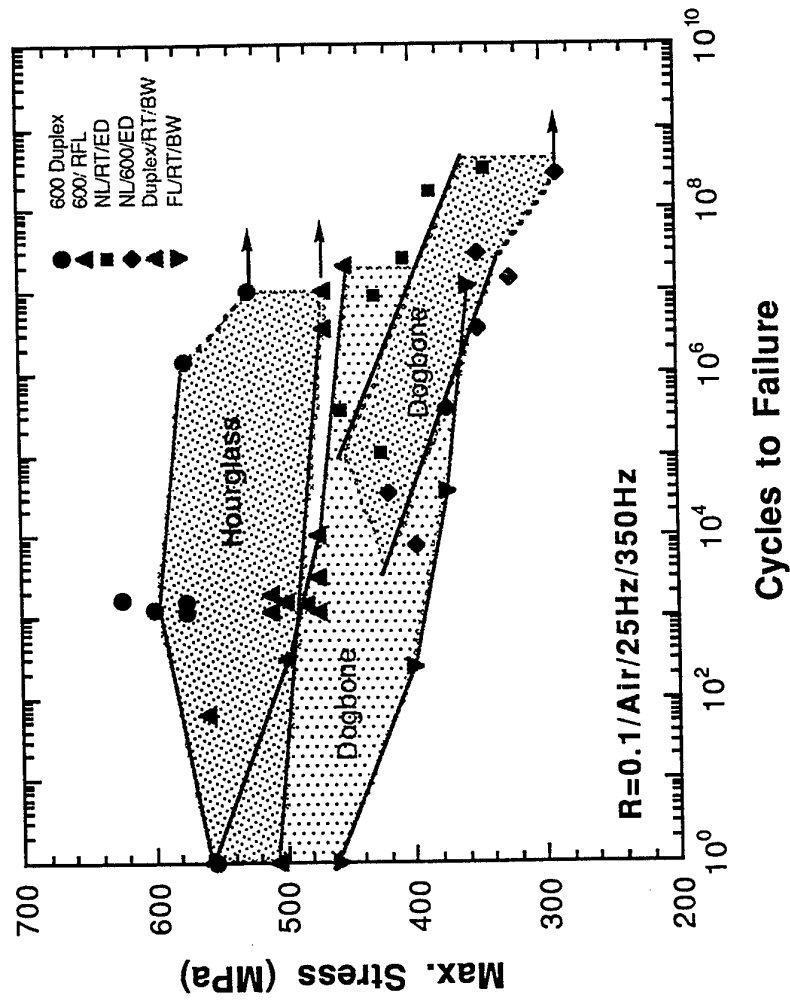
Away from Cl

$$\sigma_m = 625 \text{ MPa} / c_f = 1629$$

$$\sigma_m = 575 \text{ MPa} / c_f = 1.36 \times 10^6$$

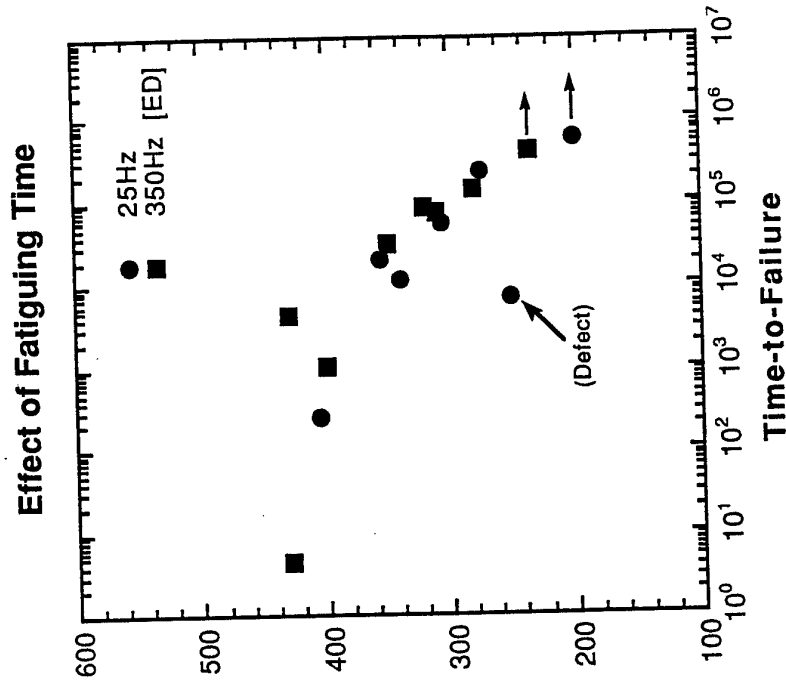
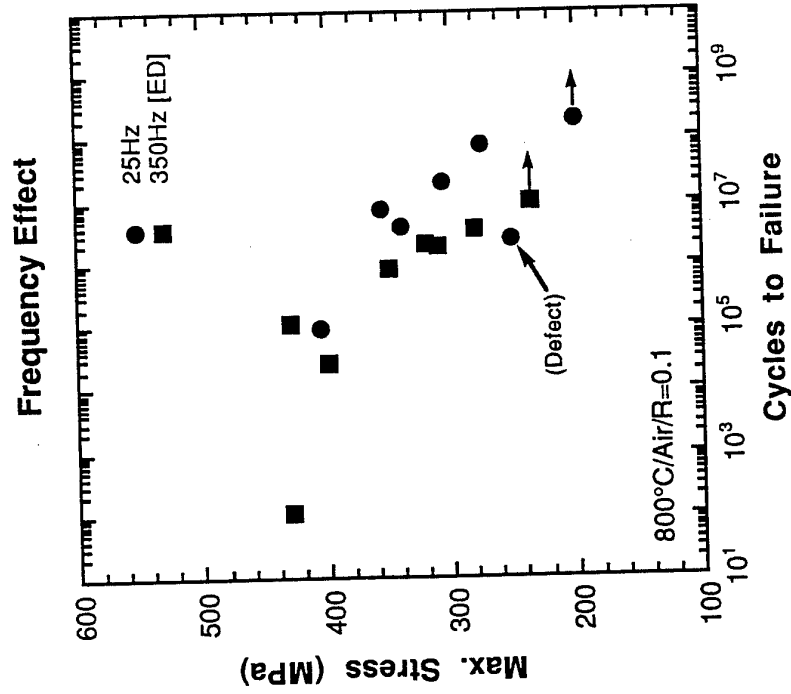
Fatigue Fracture of a Duplex Alloy K5 at 600°C in Air
(R = 0.1; UTS = 583 MPa)

Specimen Geometry Effect at <BDTT



HCF of Alloy K5 in Duplex at 800°C

(Effect of Frequency and Fatiguing Time)



Effect of Frequency on HCF

(at 800°C)

High Stress Regime ($\sigma_{\max} > \sigma_y$)

Frequency-dependent (need investigation)
High-rate deformation

Low Stress Regime ($\sigma_{\max} < \sigma_y$)

Frequency-independent
Time-dependent
Creep deformation important

Creep Fatigue

Suggested at Low Stresses

Mean Stress: $\sigma_{\text{avg}} = (\sigma_{\max} + \sigma_{\min})/2$

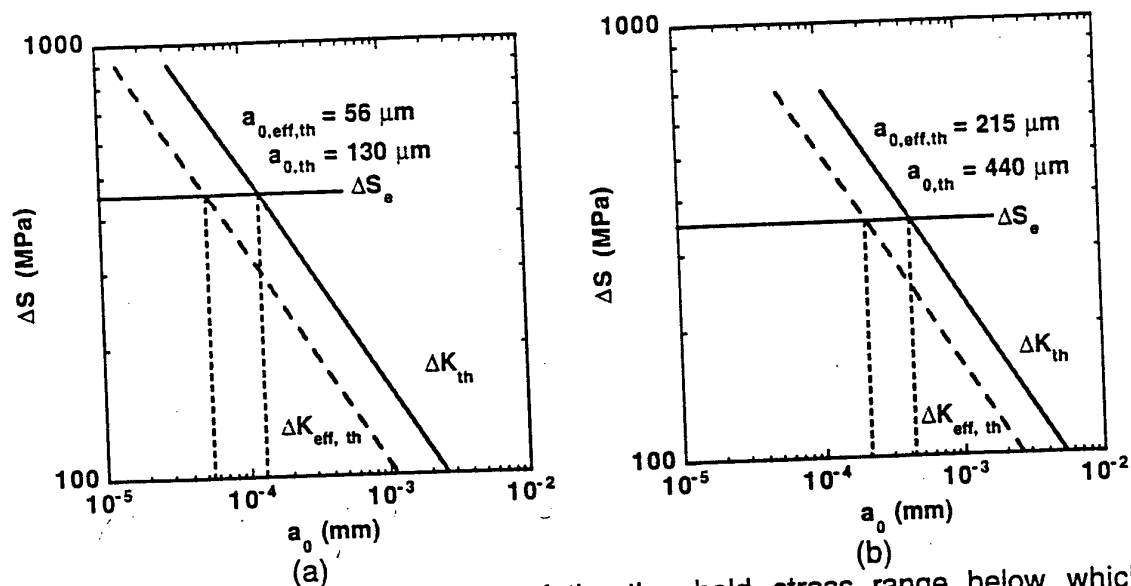
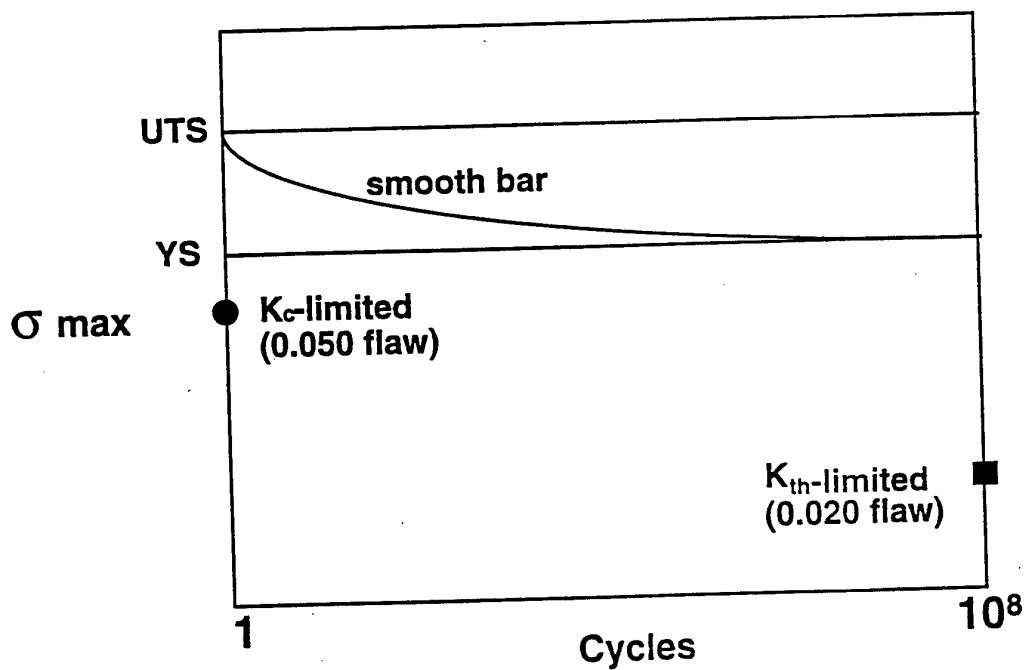
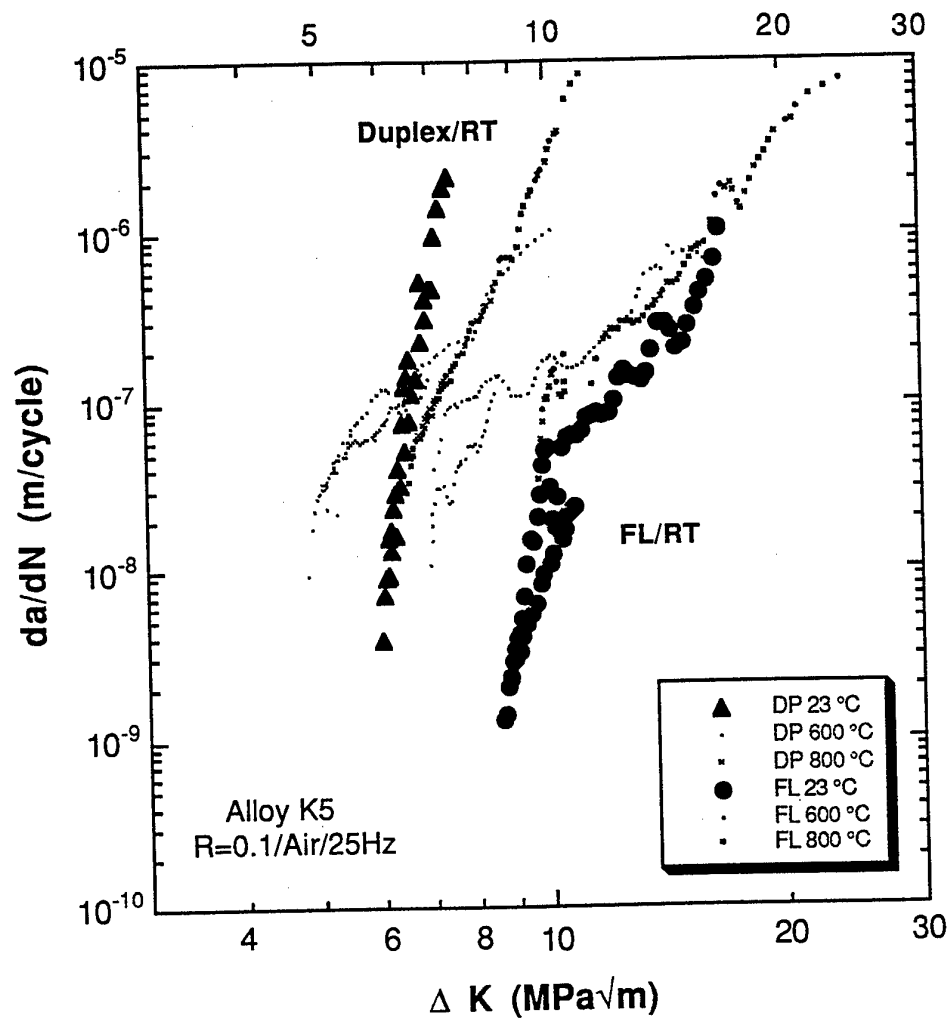


Figure 10. Crack-size dependence of the threshold stress range below which specimen failure will not occur in the alloy K5 in the (a) duplex and (b) lamellar conditions.



FCG of Alloy K5



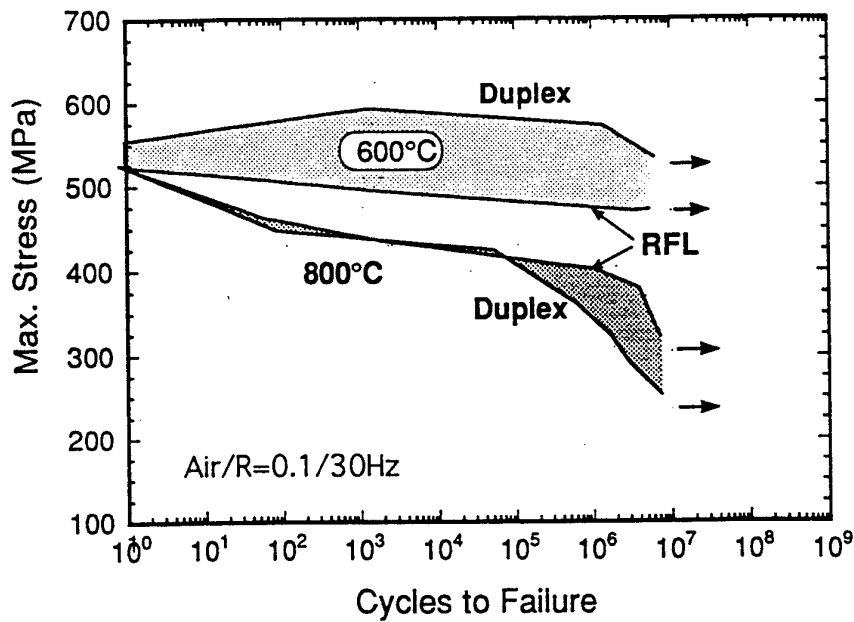
Fatigue Deformation and Failure

- Fatigue behavior in gamma alloys consists of:
 - Deformation period** (remarkably long),
 - Crack initiation and growth** (to a critical size)
 - Rapid crack propagation** (to failure)
- Below BDTT, flat SN curves are observed. The fatigue strength is controlled by tensile properties.
 - Duplex microstructure*** (preferred)

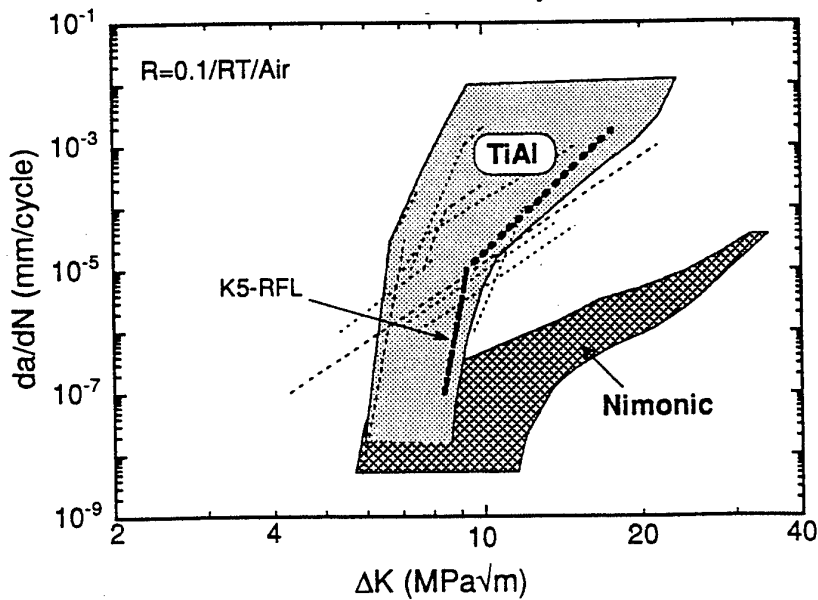
Above BDTT, fatigue life depends on tensile deformation behavior under high applied stress ($>Y_S$). Under low stresses ($<Y_S$), fatigue strength appears related to creep resistance.

 - Fully-lamellar microstructure*** (preferred)
- Fracture takes place transgranularly below BDTT and boundary fracture becomes predominant at higher temperatures.

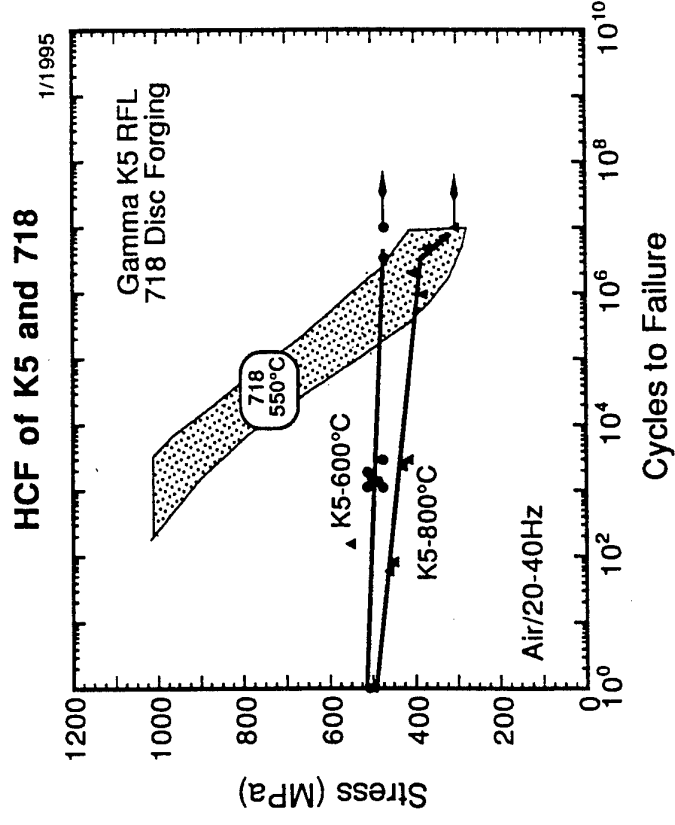
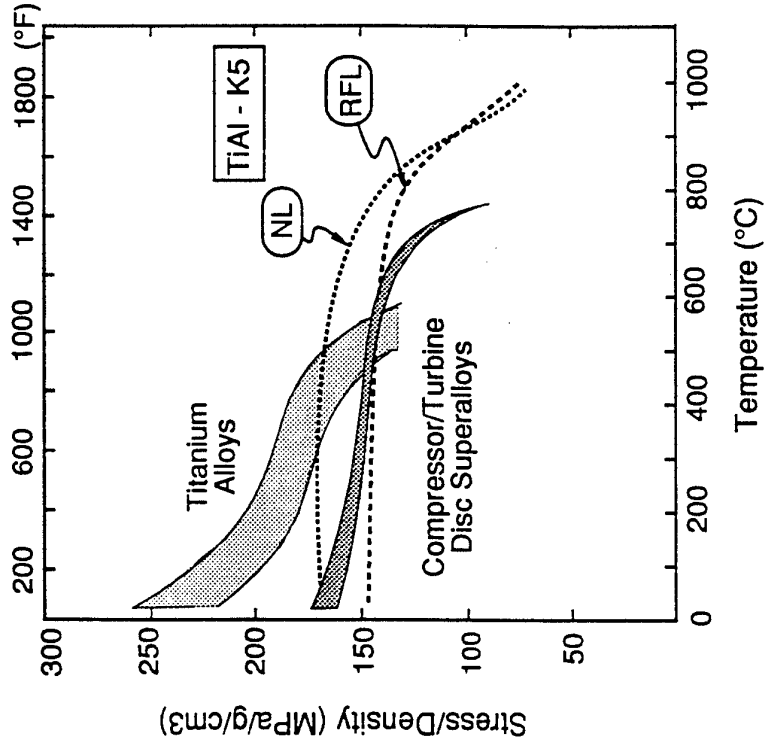
Fatigue Behavior



FCG Rates of TiAl Alloys and Nimonic



Alloy K5 vs. Disk Superalloys



Alloy Design

Alloy Selection

Microstructural Optimization

Considerations

- Mechanical Data and Behavior
- Damage-Tolerance & Life-Prediction
- Microstructural Controllability

Derive Optimum Microstructures

Devise Process & Treatment Schemes

Chemistry Modification

Promote Desired Microstructures

Improve Mechanical Behavior

Enhance Environmental Resistance

Design of Microstructures

Property Requirements

Dimensional Considerations

Component-Specific Microstructures

Scaled-up Process Development

Designed Microstructures

Refined FL (RFL)

Alloy Modification
Innovative Heat Treatments

TMT Lamellar (TMTL)

Boron Addition
Heat Treatments

TMP Lamellar (TMPL)

Extrusion
Forging
Aging

****Aligned Lamellar****

Directionally Solidified (DS)
Directionally Worked : DELM; DFLM

Other Types: Under Exploration

Chemistry Modification

(Standard: NG, DP, NL and FL)

Optimized Microstructural Features

(Wrought Alloys)

Lamellar Structure Base

Grain Size: 50-400 μm

GB Morphology

Slip Transmission
Bond Strength

Lamellar Spacing < 2 μm

Strength; Strain-to-Failure
Toughness; Creep

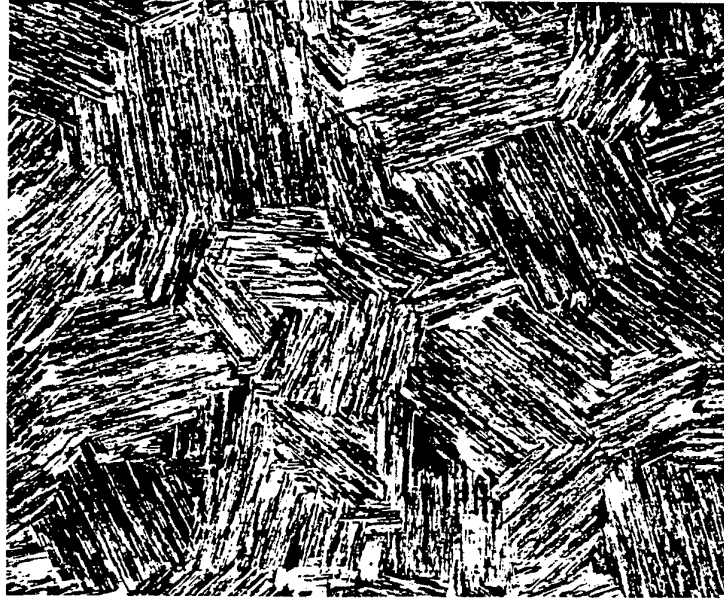
α_2 **Volume Fraction:** 5-30 %

Strength; Ductility; Toughness
Anisotropy

Texture Consideration

Duplex Microstructures (?)

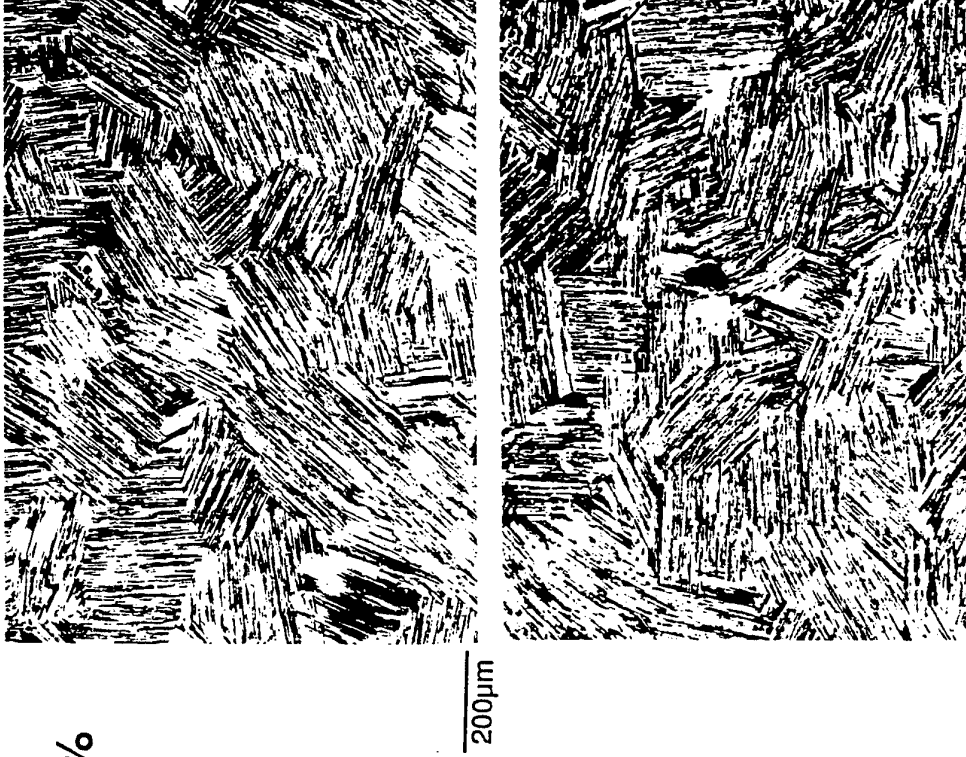
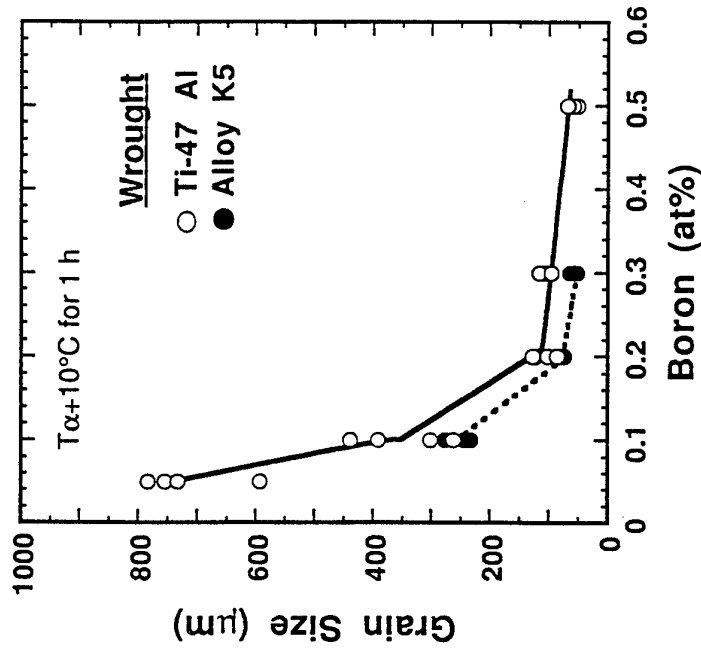
RFL vs. TMTL Microstructures

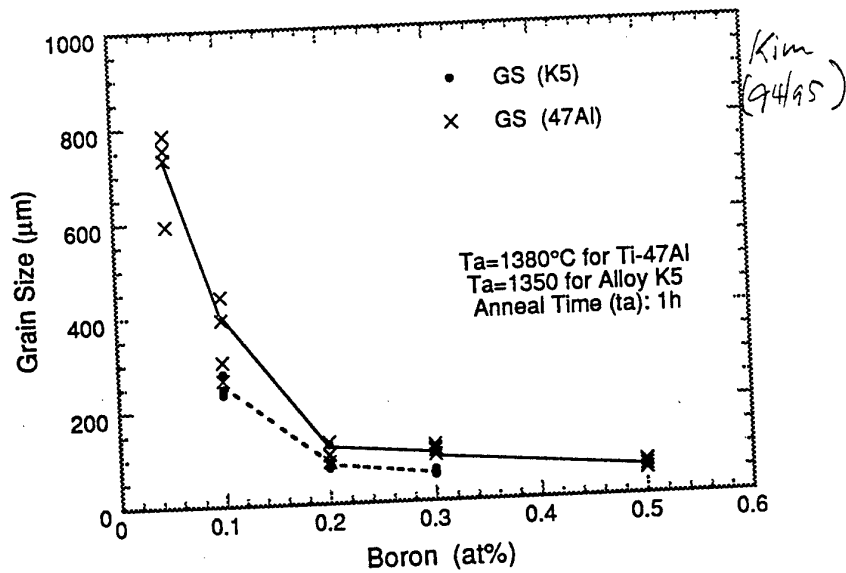


100 μm

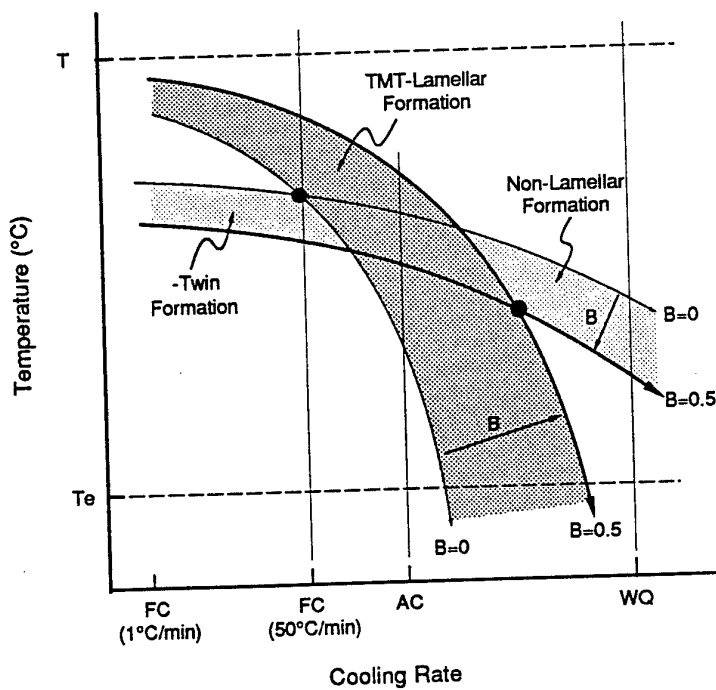
TMT Lamellar Microstructures

Wrought Processed Alloys
Boron Additions: 0.05-0.5 %
HW plus Alpha Treatment
Advantages/Disadvantages

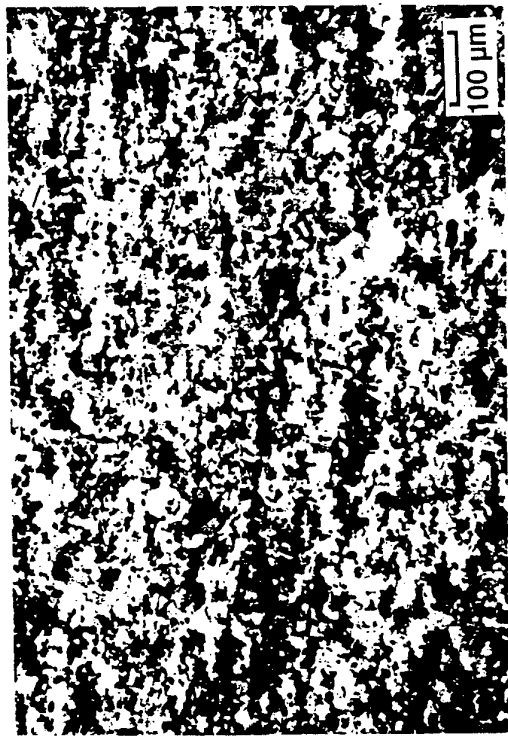




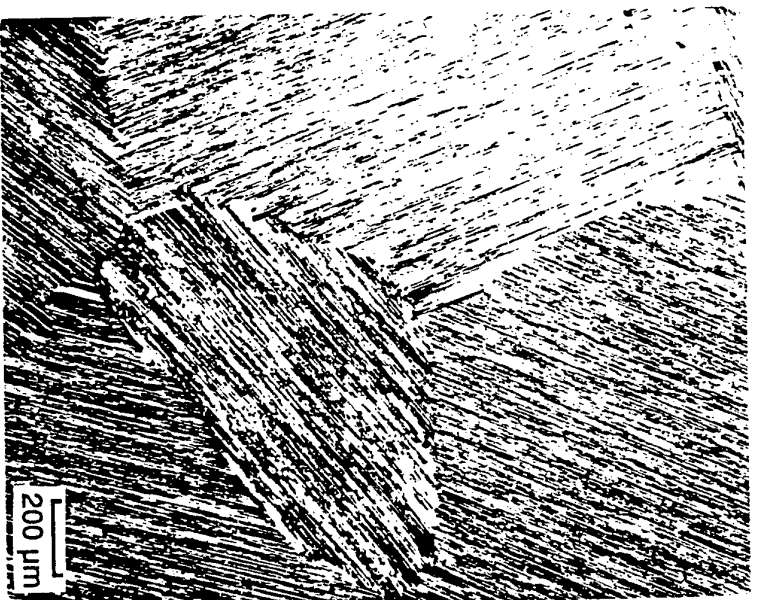
GS vs Boron Content in Gamma Alloys



Cooling-Rate and Boron -Content on Alpha Decomposition



Alloy K1: As-Forged; Near Gamma; Duplex; and TMTL microstructures



Ti-47Al-0.05B



Ti-47Al-0.10B



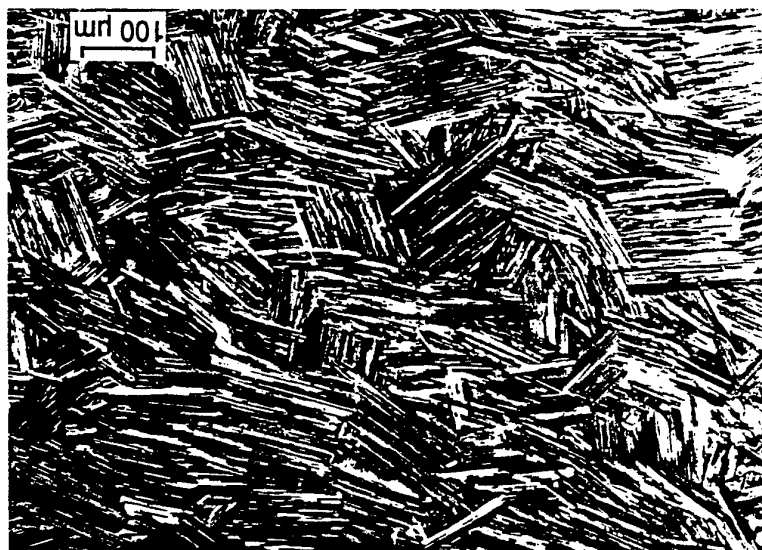
Ti-47Al-0.24B

Forged and TMT-Lamellar Treated (1370°C/1h/FC/1000°C/AC)

100 μm



FC/900°C/AC



FC/1300°C/AC

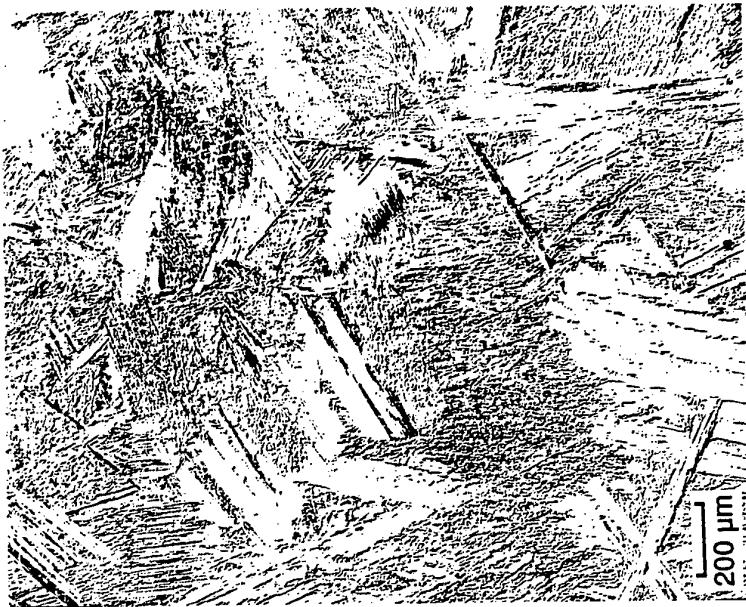


AC

Alloy K7: Alpha-Treated (1390°C/30min) and Cooled Differently

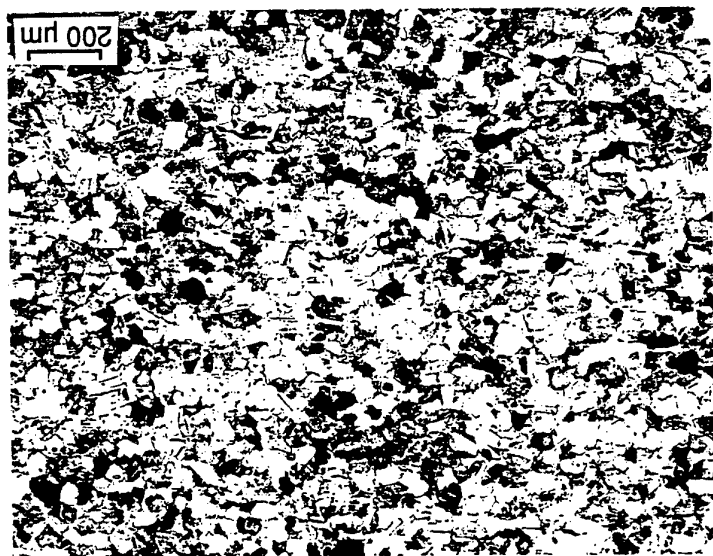


FC/1200°C/AC

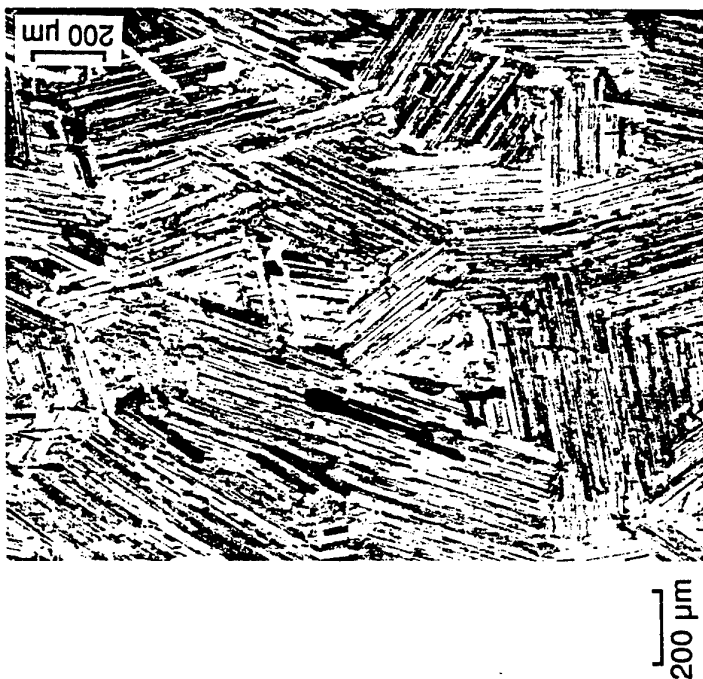


AC

Alloy K6: Alpha-Treated (1370°C/1h) and Cooled Differently

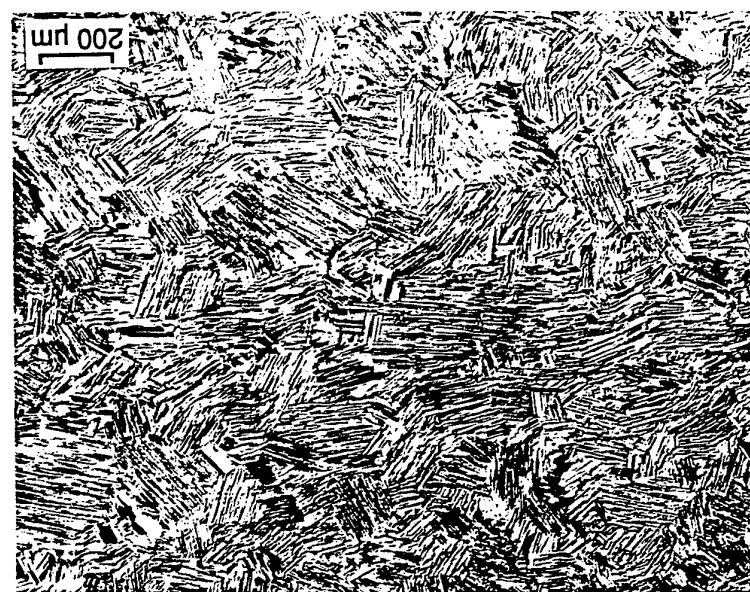
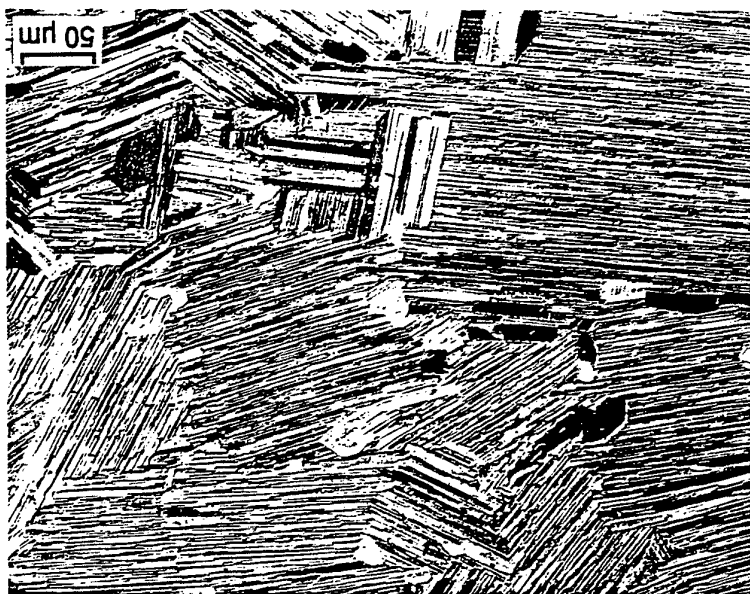


Duplex



TMTL

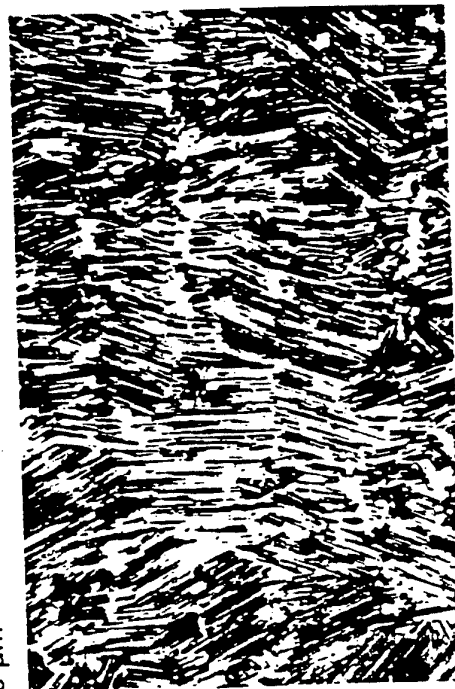
Alloy K2 (Ti-46.8Al-2Cr-4.0Nb-0.3B): Boride Distribution



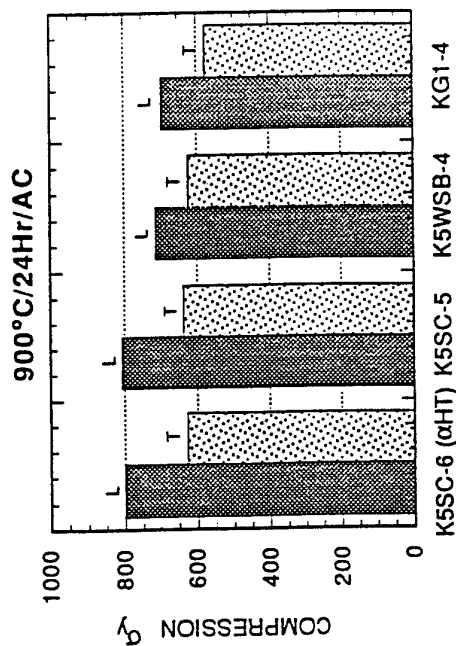
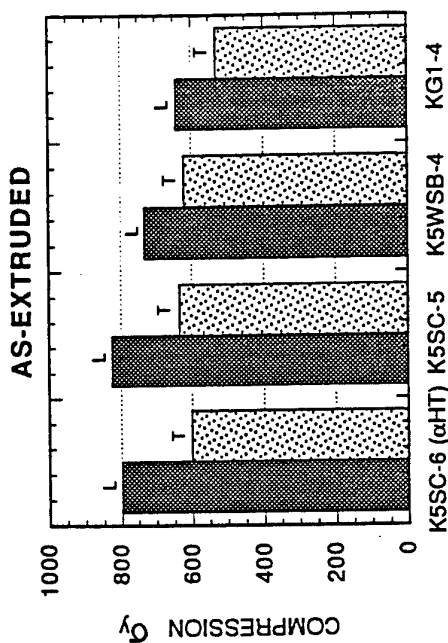
Alloy K7: TMT-Treated (1390°C/1.5h/AC) and Annealed (1300°C/24h/AC)

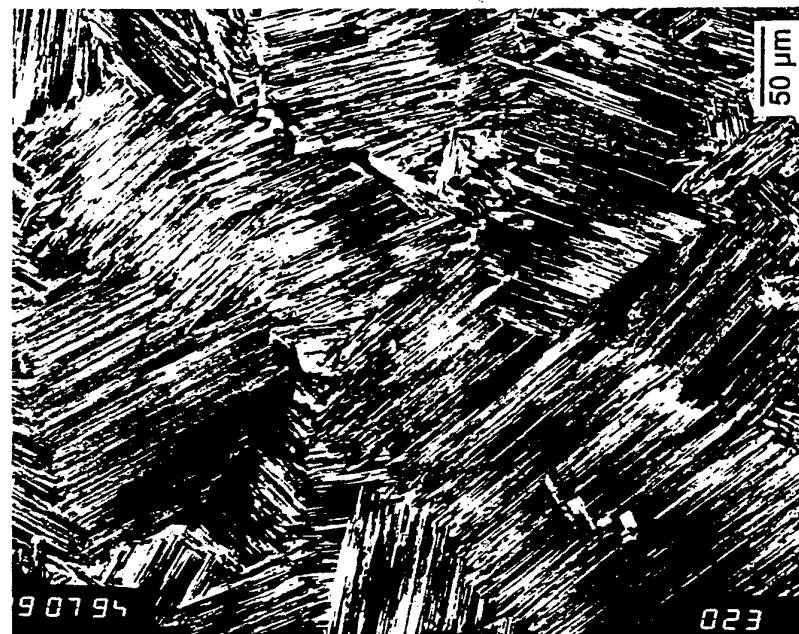
TMP Lamellar Microstructures

Time (qs)



50 μ m





K5SC Alloy TMPL Extrusion LT-Section



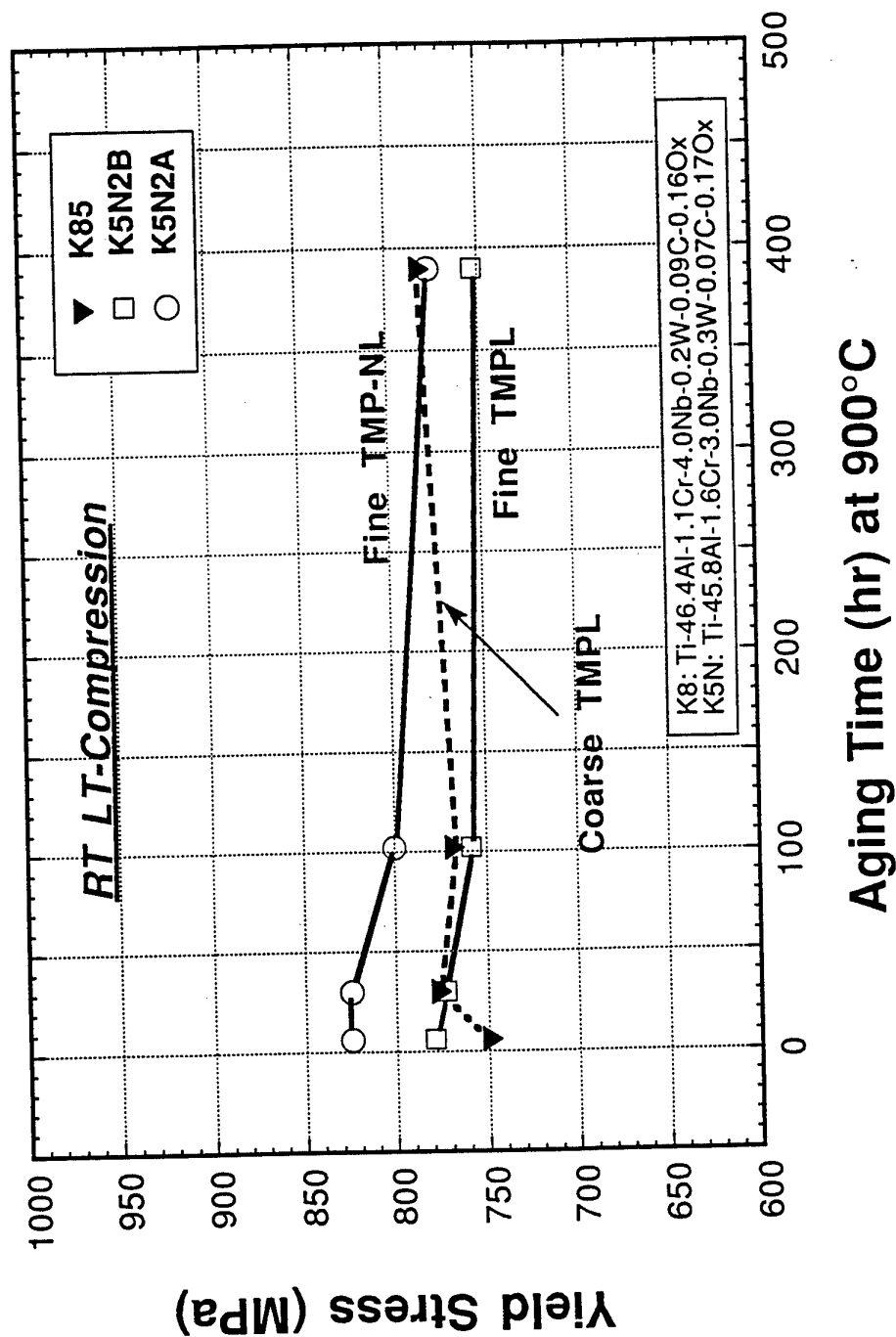
Transverse



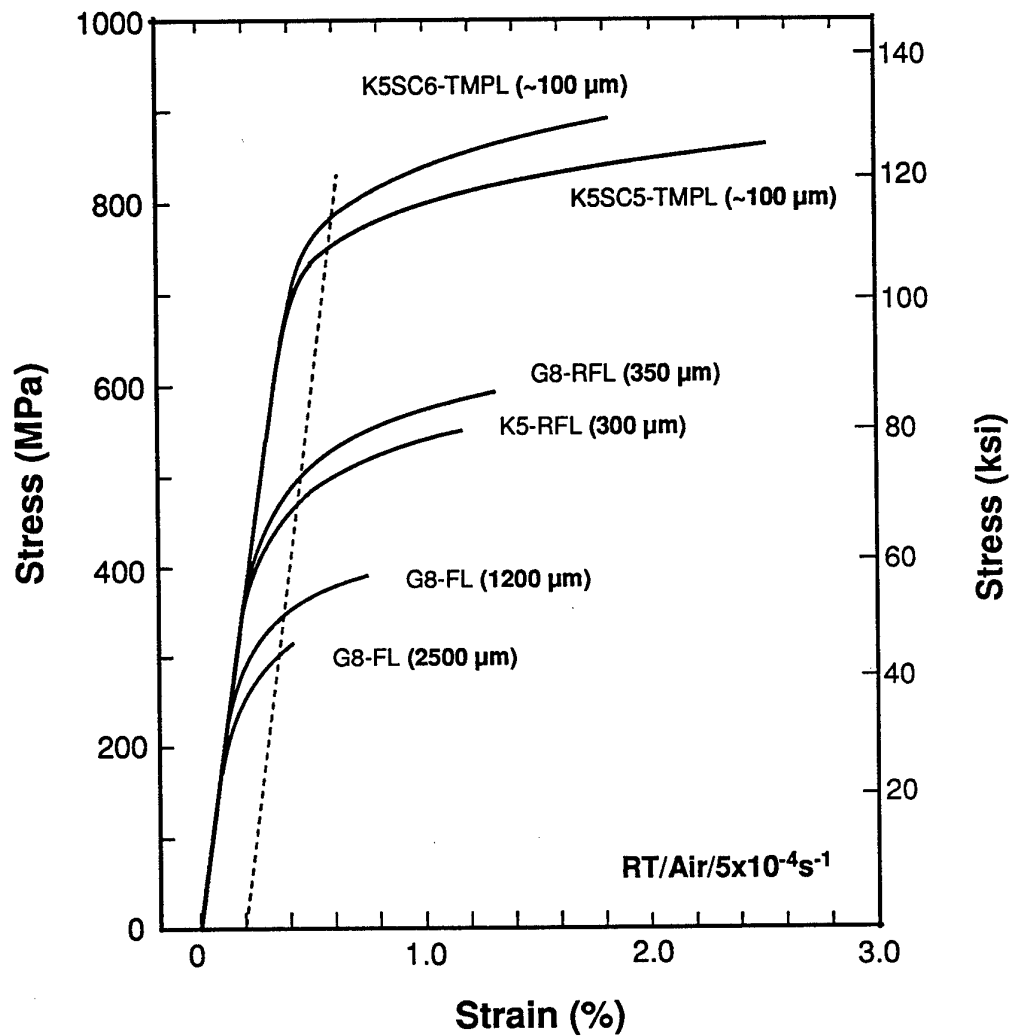
Longitudinal

A TMP Microstructure in a 4822 Extrusion

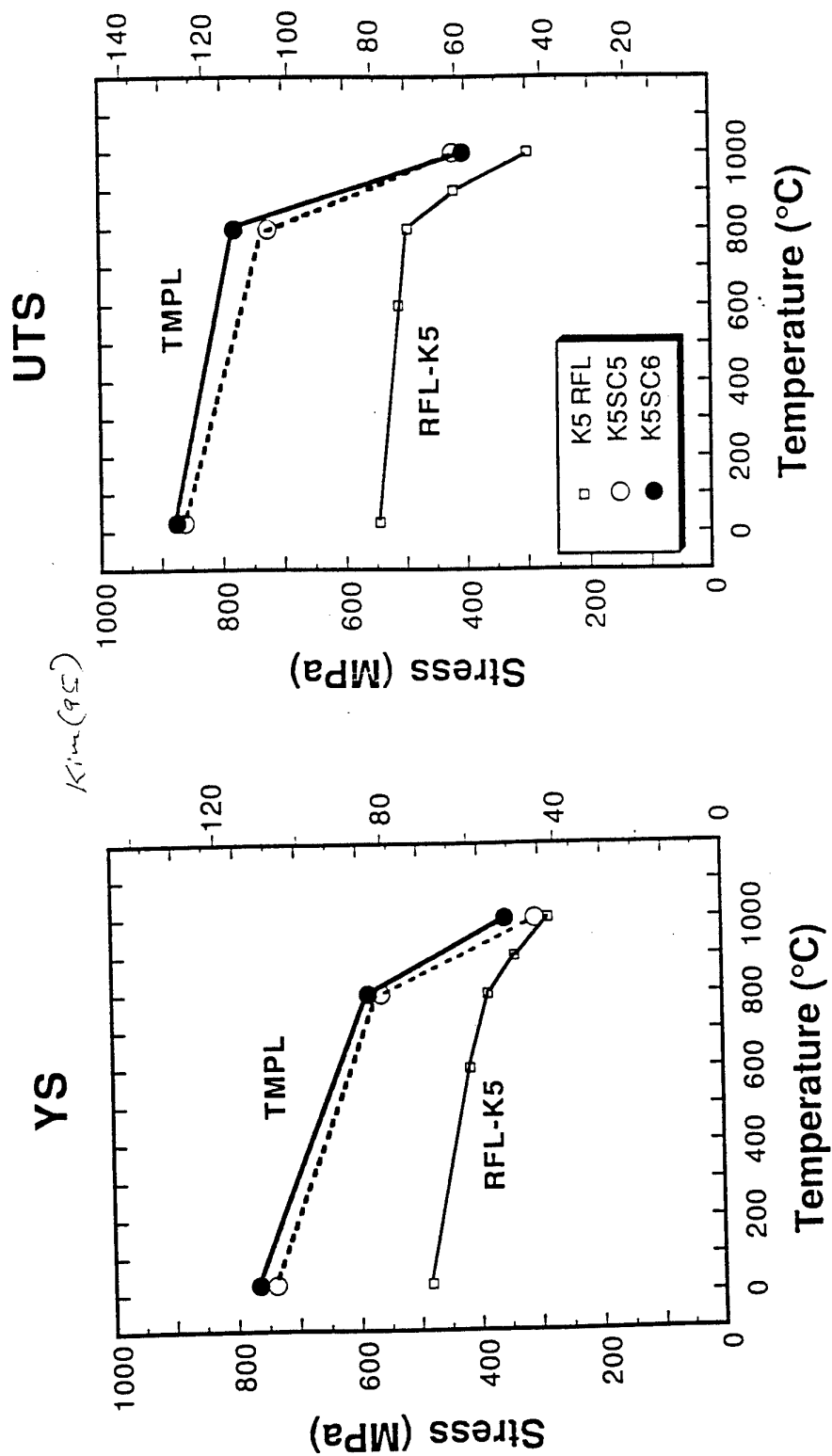
Thermal Stability of TMP Lamellar Extrusions

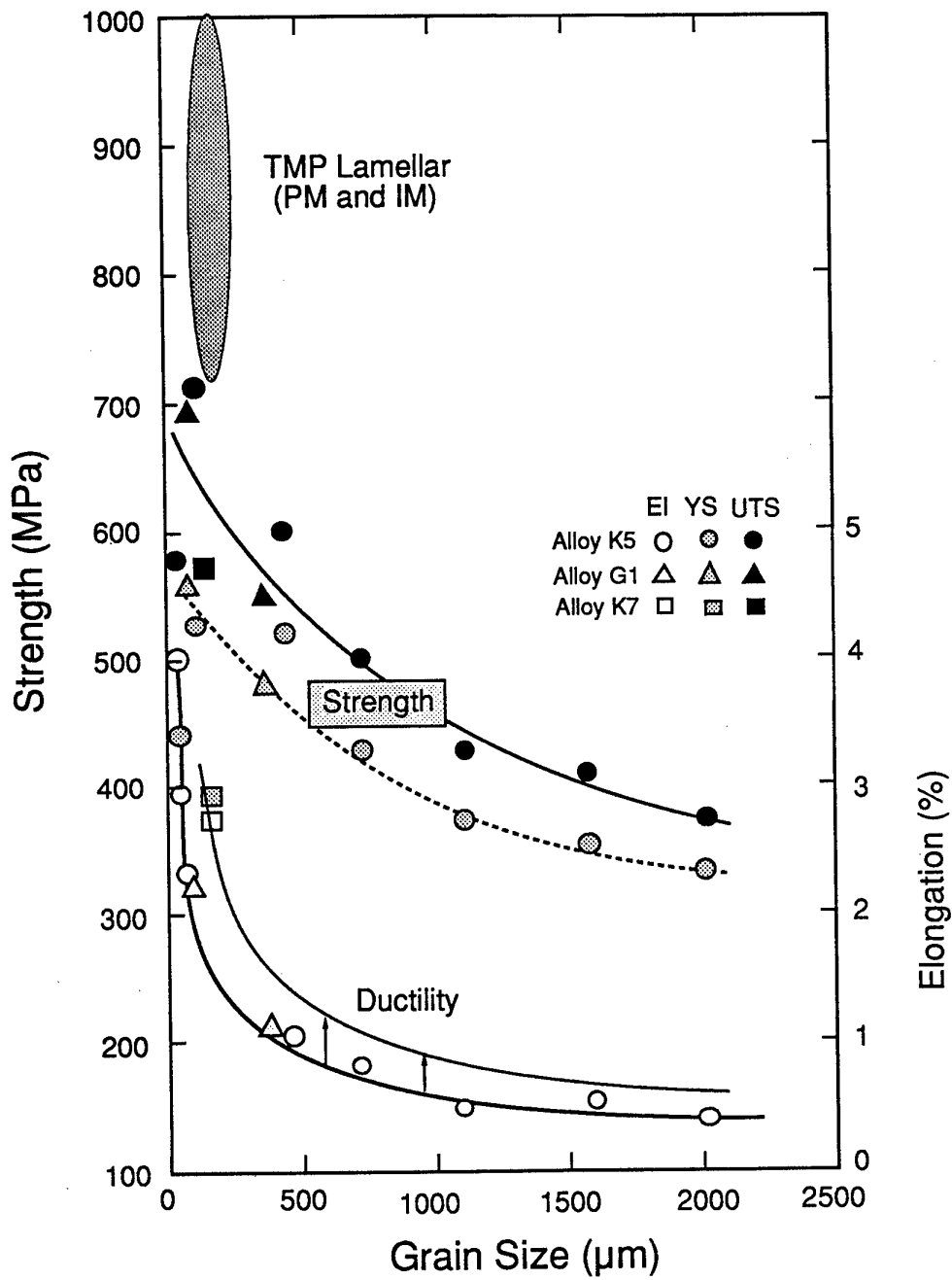


Flow Curves of Lamellar Alloys



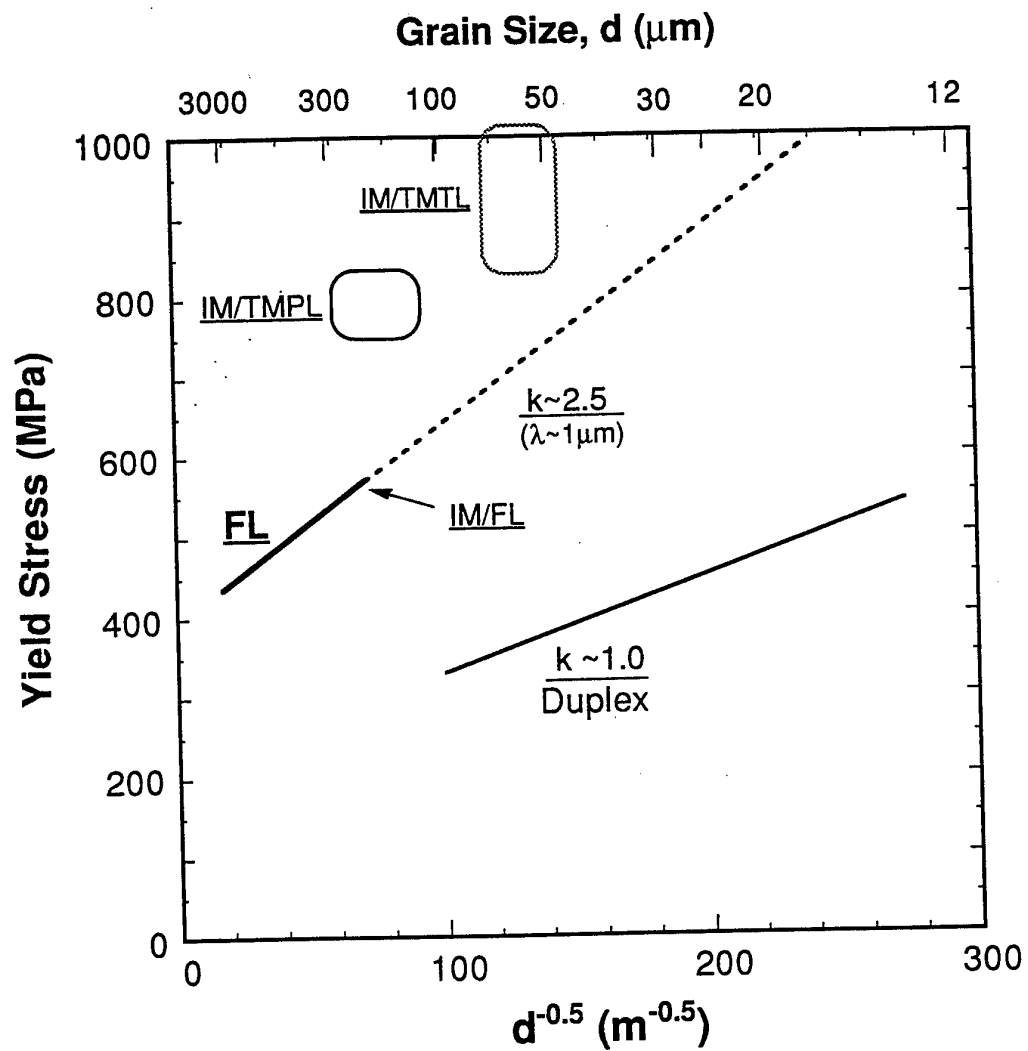
Strengths of RFL/TMPL Gamma Alloys

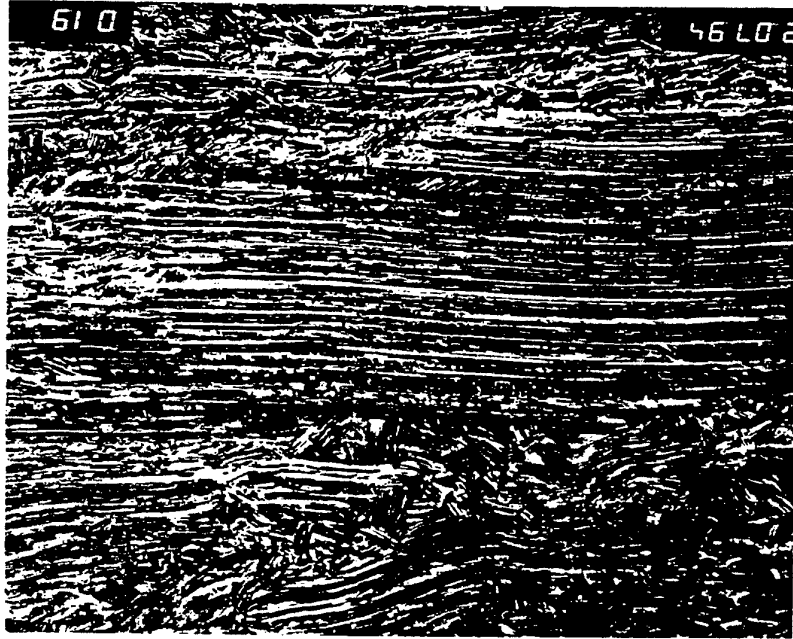




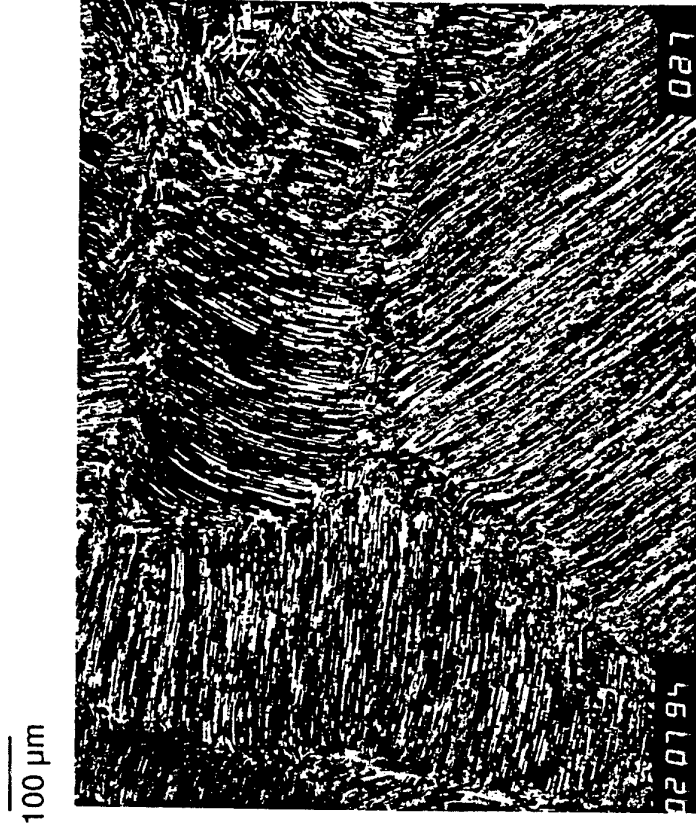
Microstructure on RT Tensile Properties

GS/LS/YS Relations in TiAl FL Alloys



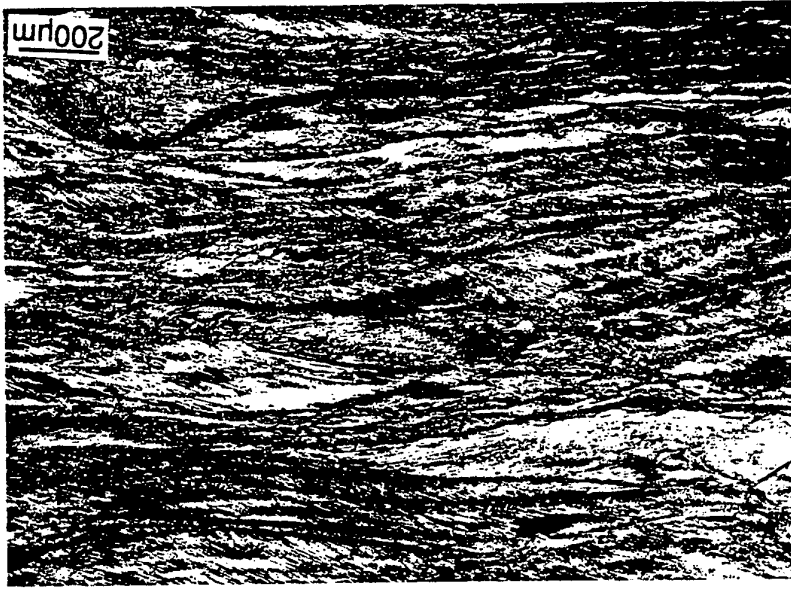


Longitudinal (L)

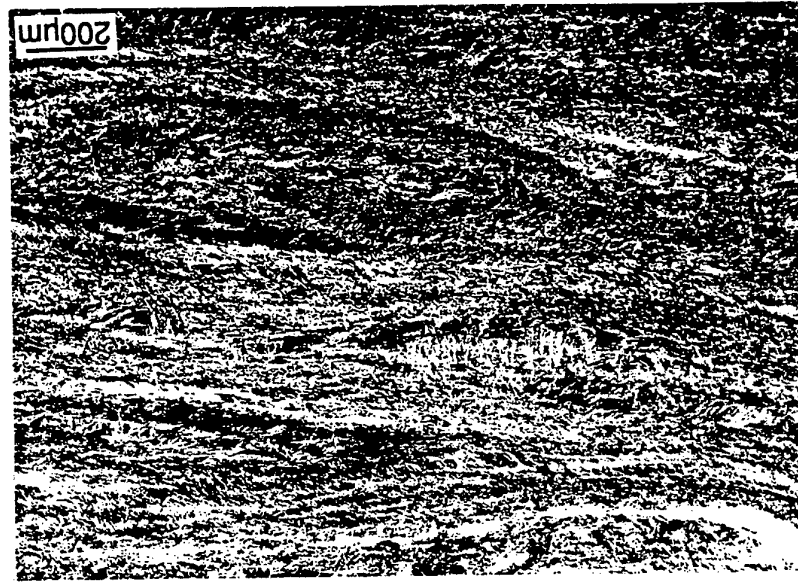


Long-Transverse (LT)

Alloy K8 TMP-Lamellar Extrusion



6



18

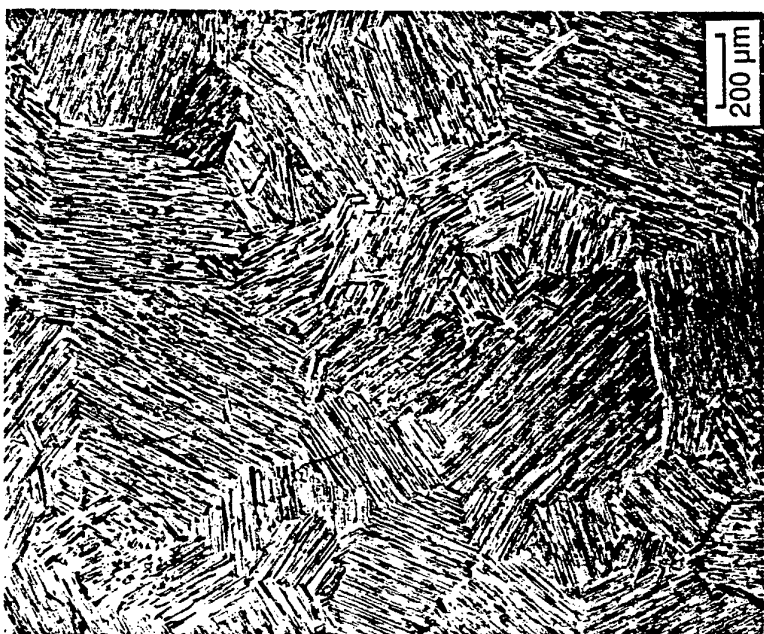
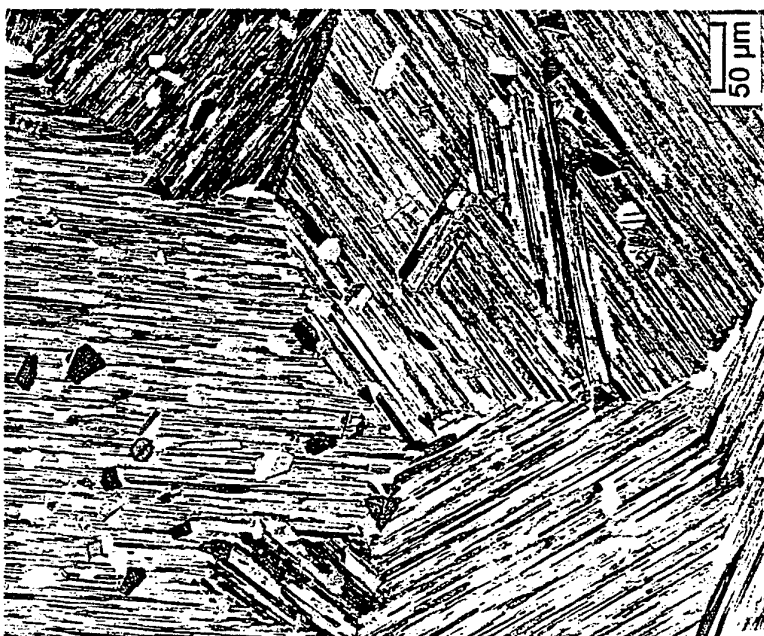


60

Alloy K5S: Effect of Ram Speed on the Alpha-Forged Microstructure



K5S (Ti-46.2Al-2Cr-3Nb-0.2W-0.2Si): Directionally Alpha-Forged



A Discrete Lamellar Structure in Alloy K5

250 μ m



FC: YS/UTS/ ϵ_f =293MPa/310MPa/0.14%



FC: 297/360/0.36



AC: 460/543/0.82



WQ: 516/579/0.5

Cooling Rate vs Microstructure/Tensile-Properties in α -Treated Alloy G8

+



WL/MLL

Metals & Ceramics Division

Gamma Microstructure/Property Relationships:

<u>STRUCTURE</u>	<u>YEAR</u>	<u>YS</u> (ksi)	<u>UTS</u> (ksi)	<u>EL</u> (%)	<u>K</u> (ksi ^{1/2} /in)	<u>CREEP</u> (<u><950°C</u>)
Duplex (G+L)	1988	65	80	3-4	12	Fair
Nearly Lamellar	1990	90	105	2-2.5	14	Fair
Fully Lamellar	1990	50	75	0.4-0.9	22-30	Very Good
Cast Nearly Lamellar*	1991	43	58	1.4-2.0	23-28	Good
TMP Lamellar	1991	85	100	2-2.5	25-30	Good

*Howment Co,
Cast Ti-48Al-2Mn-2Nb

**TMP LAMELLAR STRUCTURE HAS
BEST BALANCE OF PROPERTIES**

Properties of Titanium-Base Alloys and Superalloys

Property	Ti-Base	Ti3Al-Base	TiAl-Base	Superalloys
Structure	hcp/bcc	DO19	L10	fcc/L12
Density (g/cm ³)	4.5	4.1-4.7	3.7-3.9	7.9-8.5
Modulus (GPa)	95-115	110-145	160-180	206
Yield Strength (MPa)	380-1150	700-990	350-600	800-1200
Tensile Strength (MPa)	480-1200	800-1140	440-700	1250-1450
Ductility (%) at RT	10-25	2-10	1-4	10-25
Ductility (%) at HT(°C)	12-50 (550)	10-20 (660)	10-60 (870)	20-80 (870)
Fracture Toughness (MPa/m) at RT	30-60	13-30	12-35	30-90
Creep Limit (°C)	600	750	750a-950b	800-1090
Oxidation Limit (°C)	600	650	800 ⁺ -950 ⁺	870 ⁺ -1090 ^{**}

a Duplex; b Fully-lamellar microstructures; * Uncoated; + ** Coated; + Expected

Component Forming

(Wrought Processing)

Turbine Engine Components

Blades

- Alloy/Microstructures
- Mill product + Machining
- Impression Forging to NNS
 - Isothermal
 - Hot-Die Forming
- Heat Treatment

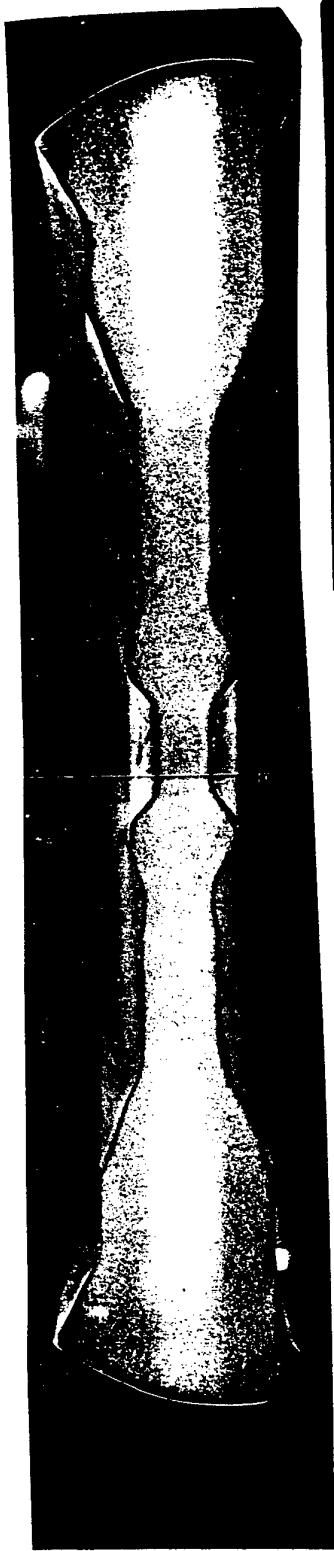
Disks

- Mill Product + Machining
- Impression Forging to NNS
 - Isothermal
 - Hot-Die Forming
- Heat Treatment

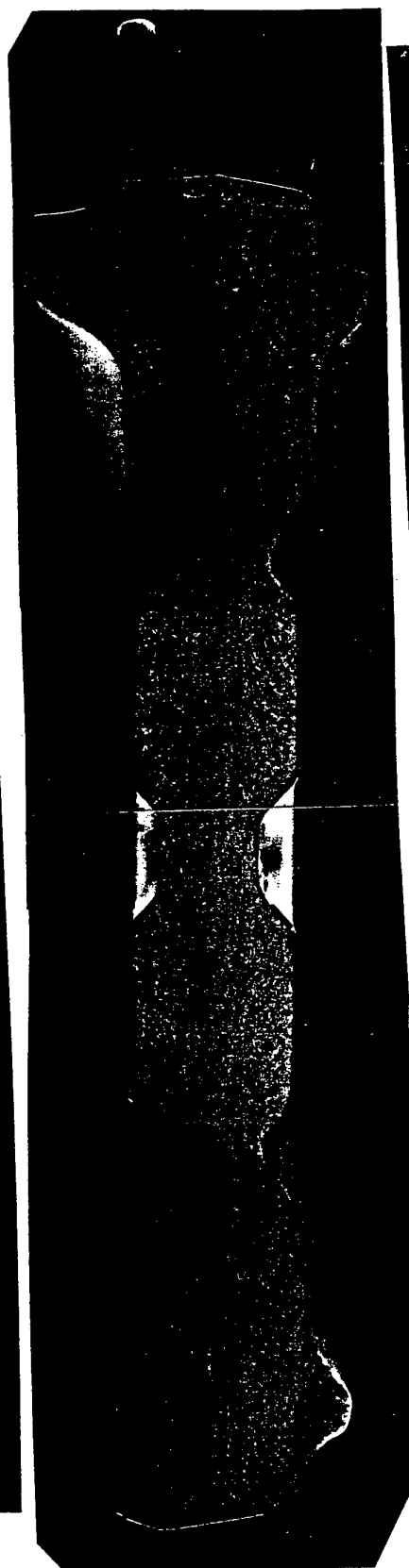
Engine Valves

Automotive Engines

Aircraft Engines



687



3882



3880

W

Automotive Valve Forming

Cast Valve

Casting

Hipping

Passenger Car

Wrought Valve

Isothermal Forging

Production Die Extrusion/Forging

Preconditioning: IM; PM

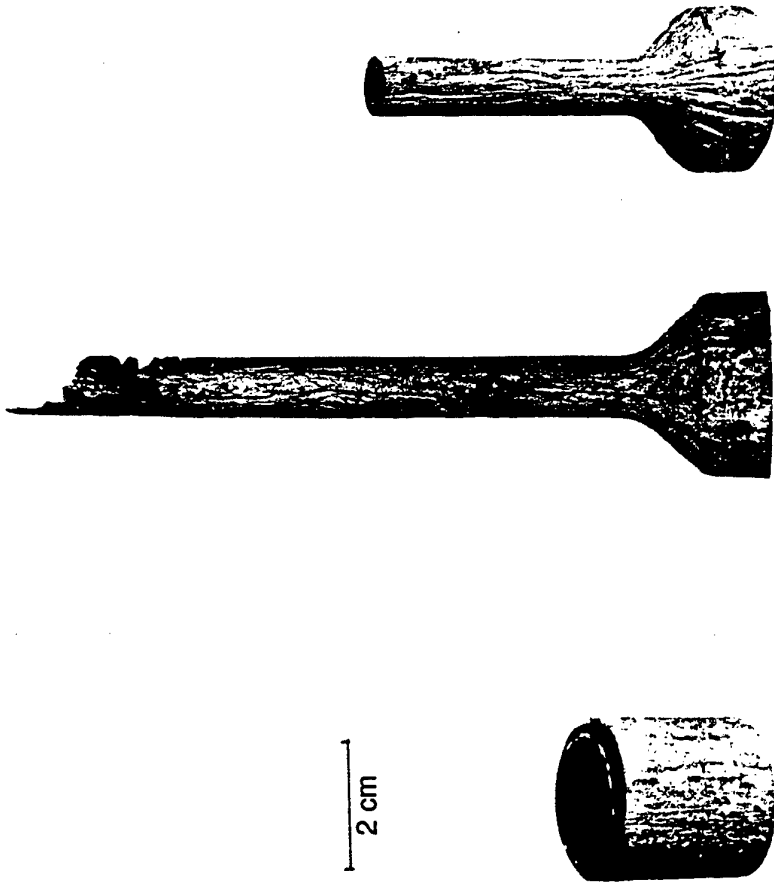
High Rate Extrusion of Preforms

High Rate Head Forging

Microstructure Control

Head/Stem Joining

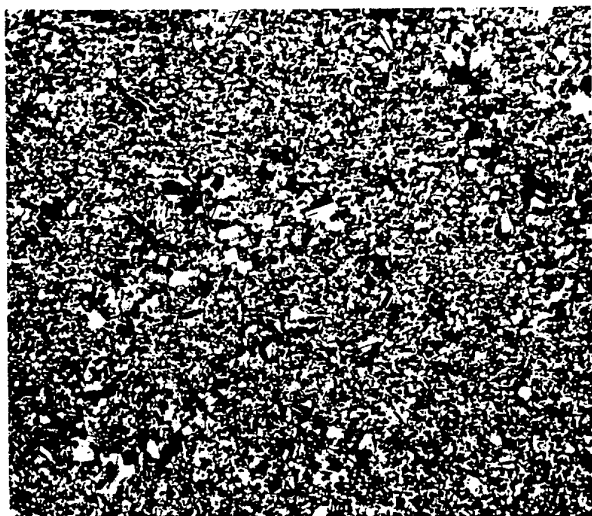
High Performance



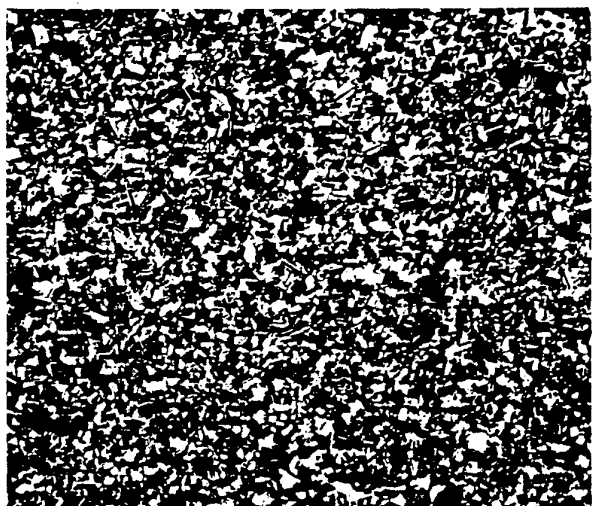
Preform

1st Step: Partial Extrusion

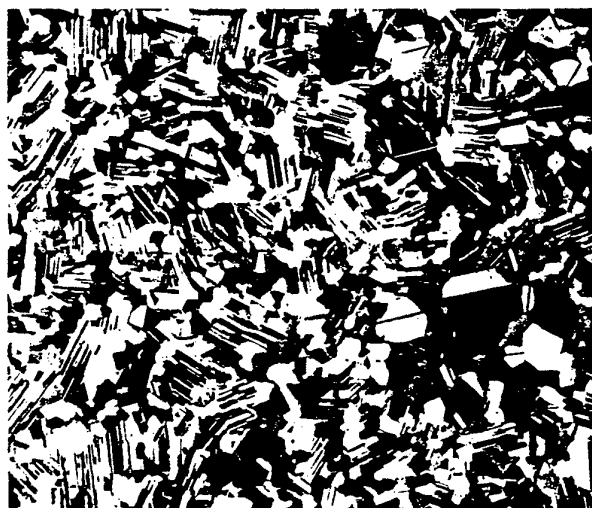
Wrought Gamma Engine Valve



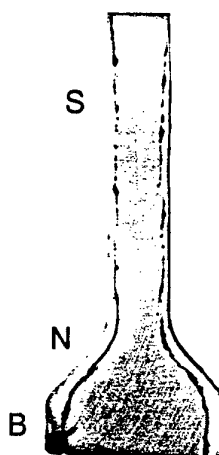
Stem



Neck



Base



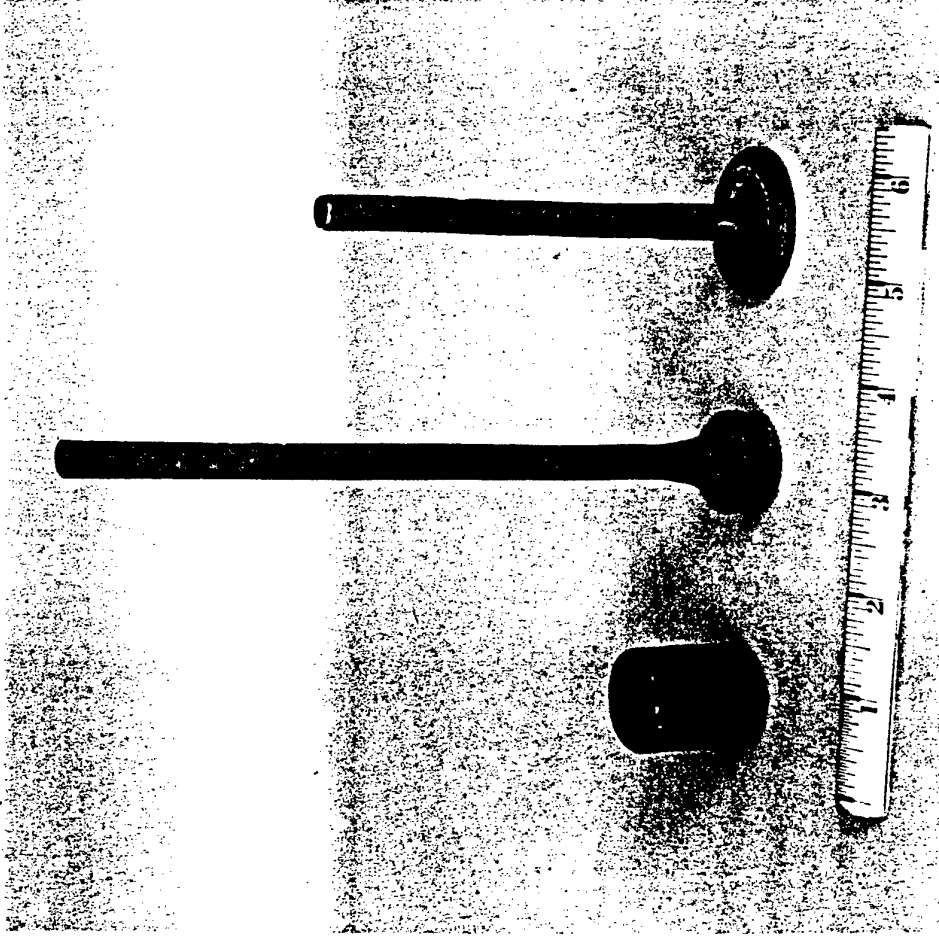
50 μm

G10 Valve Extrusion:
Transverse Sections

High-Rate (80 cm/sec)
Warm-Die (250°C)

Valve Extrusion
Head Coining

Commercial Steel Valve
Production Press (TRW)



Wrought Gamma Exhaust Valves

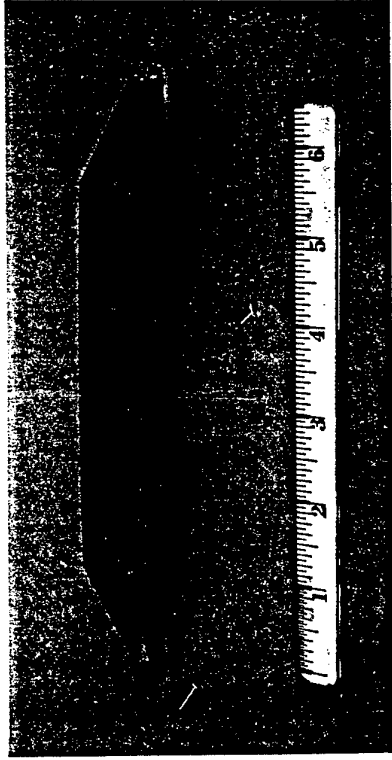
Applications

Aircraft Gas Turbine Engines

Automotive Engines

Land-Based Gas Turbine Engines

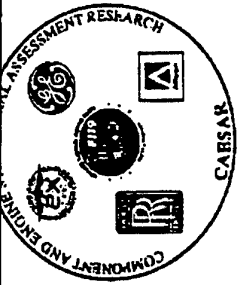
Others



Cast 4822 Gamma Transition Duct Beam
GE-90 Engine for Boeing 777

CAESAR Program

COMPONENT AND ENGINE
STRUCTURAL ASSESSMENT RESEARCH



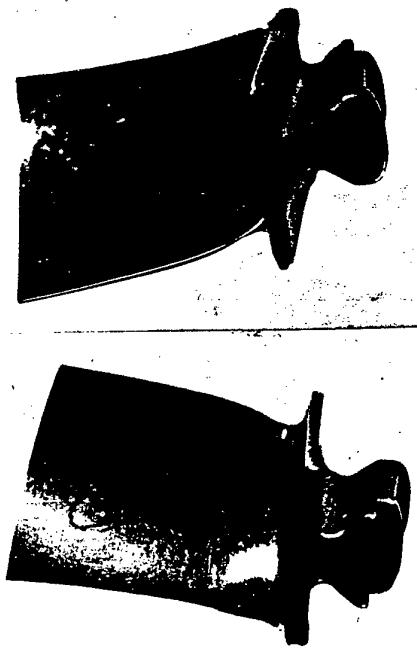
Gamma Titanium HPC 6th Stage Blades

Participants:

P&W	Cast "XD" Ti-47Al-2Nb-2Mn-0.8%TiB ₂
Rolls Royce	Cast "XD" Ti-45Al-2Nb-2Mn-0.8%TiB ₂
Allison ADC	Wrought Alloy 7
GE	Wrought Ti-48Al-2Cr-2Nb

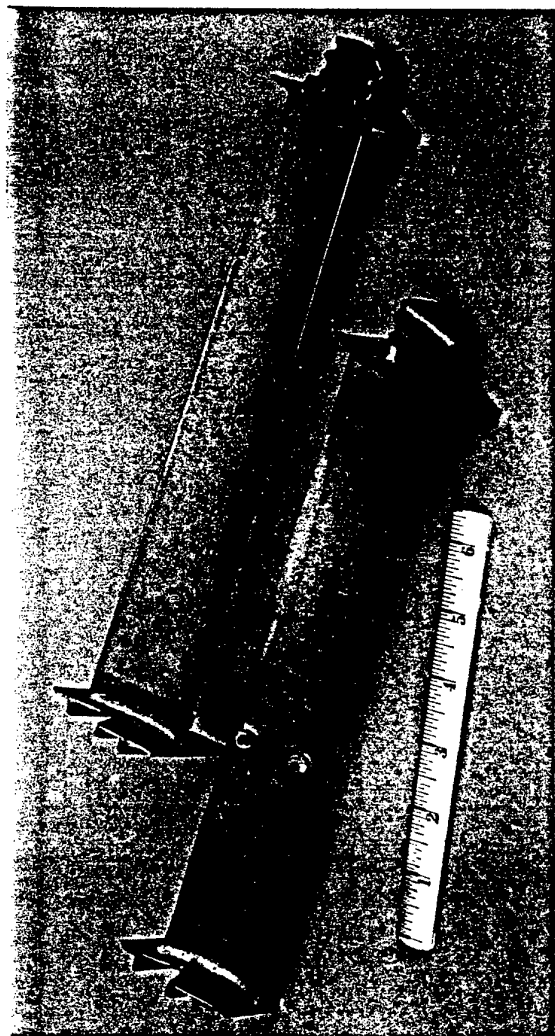
Schedule:

Design and fabrication	Jan 96
Delivery to P&W	Mar 96
Proof spin (P&W)	Aug 96
F419 Core test 100 hrs (AEBC)	Dec 96
Engine tests 2000 TAG cycles (P&W)	Jul 97
Spin pit test to failure (P&W, UK)	Dec 97



Other gamma Ti components:

- ~~HPG inner shroud~~
- ~~combustor swirler~~
- ~~nozzle tile~~



4822 Cast Gamma LPT Blades for GE CF6-80C2

**Cast and Chem-milled
Engine Tested for over 1000 cycles**

Summary and Future

Continuous Alloy Exploration/Design

Casting vs Wrought Alloys

Continuous Search for Fundamentals

Process Development

Component-Specific Alloy Design

Search for Application Areas

Understand Practicality

Collaboration/Exchange